EFFECT OF TREATING FIELD SPATIAL VARIABILITY IN WINTER WHEAT (*Triticum aestivum* L.) AT DIFFERENT RESOLUTIONS, AND ADJUSTING MIDSEASON NITROGEN RATE USING A SENSOR-BASED OPTIMIZATION ALGORITHM TO IMPROVE USE EFFICIENCY IN CORN (*Zea mays* L.)

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EFFECT OF TREATING FIELD SPATIAL VARIABILITY IN WINTER WHEAT (*Triticum aestivum* L.) AT DIFFERENT RESOLUTIONS, AND ADJUSTING MIDSEASON NITROGEN RATE USING A SENSOR-BASED OPTIMIZATION ALGORITHM TO IMPROVE USE EFFICIENCY IN CORN (*Zea mays* L.)

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Chapter I

EFFECT OF TREATING FIELD SPATIAL VARIABILITY IN WINTER WHEAT (*Triticum aestivum* L.) AT DIFFERENT RESOLUTIONS

ABSTRACT

Variable rate application is one of the emerging technologies for improved nitrogen use efficiency (NUE) of grain crops. This study was conducted to determine the scale at which spatial variability should be treated using an in-season nitrogen fertilization optimization algorithm (NFOA). The treatments included variable N rate applications at three resolutions (0.84, 13.37 and 26.76 m^2), a fixed N rate at 90 kg ha^{-1} applied preplant and midseason, and a check plot (0-N). Treatments were arranged in a completely randomized design (CRD) with three replications established at two locations for three years (Chickasha 2004-2006, Tipton 2004-2005, and Lake Carl Blackwell 2006). Plots treated variably were sensed at winter wheat growth stages Feekes 5 using the GreenSeeker™ hand held sensor prior to midseason fertilization. The N rate for each subplot was calculated using predicted yield potential (YP_0), response index (RI) and coefficient of variation (CV), all derived from Normalized Difference Vegetation Index (NDVI) readings. On average, the NFOA-based N rates achieved a higher NUE of 41% compared with the 90 kg ha^{-1} fixed rate applied midseason of only 33%. The highest NUE among the NFOA-based N rate treatments was 56% at 13.4 m^2 resolution. Four out of six site years resulted in higher net return when the NFOA approach was used. Savings on cost of N fertilizer ranged from $ 5 to 101, and $ 32 to 101 per hectare when compared with the fixed rate of 90 kg ha^{-1} applied midseason and/or preplant, respectively. These benefits were attributed to a large reduction in NFOA-based N rate recommendations. Treating spatial variability at 0.84 m^2 had a positive impact on net return and NUE only when the average CV (estimate of crop stand) was greater than 20%, and when the price of N fertilizer was at least $ 0.60 kg N^{-1} provided that the price of wheat grain was

$ 0.08 kg^{-1}. When NFOA was used to determine midseason N rate requirements, treating spatial variability at 13.4 m^2 resulted in increased NUE and net return.

INTRODUCTION

Liberal applications of nitrogen (N) fertilizer in crop production has led to reduction of farmers' revenues and increased human health and environmental risk. Current worldwide N use efficiency (NUE; increased grain N uptake per unit of N applied) in cereal grains averages only 33% and the unaccounted 67% of applied N is lost via g aseous plant emission, soil denitrification, surface runoff, volatilization and leaching (Raun and Johnson, 1999). Conventional N fertilization based on soil testing of representative samples from large farm areas is at fixed rates and usually applied before crop establishment. Due to spatial variability in the field, single rates may estimate N requirement far from the actual values needed to achieve a target yield goal, resulting in excess N application at certain locations in the field. Moreover, N in soils changes with time as environmental conditions highly influence mineralization and immobilization, the predominance of one process over the other determines the level of available N for plant use.

To meet the demand of the projected 7.5 billion world population in 2020 (FAO data, 2004), wheat production needs to increase beyond the current yield level of 556 million tons (FAO data, 2003) by 40% (Rosegrant et al., 1997). Since the potential of the Green Revolution has been exhausted and there is a continuous decline in arable land, future gains in wheat production and revenues will have to come from increased productivity at reduced input costs.

Farmers often apply N fertilizer in excess to avoid deficiency and to ensure that the N requirements of the crop for the whole cycle are met. According to FAO (2005), the present total consumption of nitrogenous fertilizer in the world is estimated to be 85.1 Mt N yr^{-1}. For the past 34 years, agricultural food production was doubled due to a 6.87-fold increase in N fertilization (Tilman, 1999). Improper N fertilizer management has resulted in greater use of energy resources, increased production costs and increased environmental and human risk (Sharpe et al., 1988). Rabalais et al. (2001) reported that excessive fertilizer N application has exacerbated hypoxia within the Gulf of Mexico. Moreover, high N rates may result in poor N uptake and thus decreased N use efficiency (Sowers et al., 1994). The benefit of increasing N use efficiency includes increased profit by reducing N fertilizer inputs and reduction of environmental and human health risks associated with nitrate contamination (Huggins and Pan, 1993).

Several studies were conducted to develop management systems that would increase N use efficiency. Proper timing of application and adequate N rates are all important considerations in providing what the plant needs and can therefore improve N use efficiency. Wheat farmers in the Great Plains typically apply fertilizer N either one-time before planting, or split in small amounts before planting followed by a late-winter or early spring topdressing (Kelley, 1995). Similarly, Cassman et al. (1992) showed that pre-plant and in-season N fertilizer management improved both yield and protein content of wheat. Split applications maximize crop utilization of applied fertilizer N throughout the growing season (Mascagni and Sabbe, 1991; Boman et al., 1995). Late-season applied N allows the farmers to adjust N rates according to crop growth and may also reduce potential N losses from leaching and denitrification over the winter. Further, many researchers have found that one-time large pre-plant applications of N fertilizer may lead to decreased N use efficiency due to losses or immobilization before plant uptake (Welch et al., 1996; and Olson and Swallow, 1984; Lutcher and Mahler, 1988; Fowler and Brydon, 1989; Wuest and Cassman, 1992). While multiple, late-season N application is an effective way of increasing NUE, the common method of using soil surface soil testing for adjusting N rate before planting is not suited for detecting late-season deficiency. In addition, environmental factors such as soil temperature and moisture affect N cycling, transformation and movement which complicate the present N status monitoring of the crop.

Remote sensing could provide an inexpensive, non-destructive and rapid assessment of crop N status in the field (Filella et al., 1995). Several studies used remotely sensed spectral measurements to evaluate plant biomass (Wallburg et al., 1982; Kleman and Fagerlund, 1987; Wanjura and Hatfield, 1987; Casanova et al., 1998; Felton et al., 2002; Bronson et al., 2003) and plant N content (Blackmer et al., 1997; Stone et al., 1996a; Bronson et al., 2003). Some researchers used spectral data to estimate crop yields using simple regression equations (Moran et al., 1997; Raun et al., 2001). Normalized Difference Vegetation Index (NDVI; Rouse et al., 1973) is one of the spectral vegetation indices used to assess plant health status and is determined by dividing the difference in reflectance in the red (670 nm) and near infrared (NIR; 780 nm) by the sum of reflectance at these two wavebands (Tucker, 1979). The NDVI was found to be a useful index to estimate crop yield of wheat (Colwell et al., 1977; Tucker et al., 1980; Pinter et al., 1981), millet, and sorghum (Bartholome, 1988). Stone et al. (1996a) and Solie et al. (1996) reported that NDVI can reliably predict both biomass and N uptake in winter wheat when measurements were done between Feekes physiological growth stages 4 and 5. Similarly, Lukina et al. (1999) were able to show high correlations between percentage of soil coverage by wheat and NDVI at these growth stages. At Feekes growth stage 5, Reeves at al., (1993) used direct in-season measurements of total N uptake in winter wheat.

Raun et al. (2002) utilized NDVI-derived in-season estimated yield (INSEY), biomass produced per day, to project mid-season N rate requirement in wheat. Compared with the mid-season flat rate of 45 kg ha^{-1}, wheat NUE was increased by >15% when mid-season N fertilization was based on INSEY. In 2005, Raun et al. proposed the use of a nitrogen fertilization optimization algorithm (NFOA) consisting of the following components: 1) INSEY, NDVI measured at Feekes growth stage 5 divided by the number of positive growing degree days or GDD = $\left[\left(\frac{T_{max} + T_{min}}{2}\right) - 4.4°C\right]$, 2) responsiveness of the wheat crop to N fertilizer that can be estimated by the ratio of NDVI readings in non-limiting N strips and the NDVI readings in the farmer practice, and 3) spatial variability using the coefficient of variations (CV) from NDVI readings. The addition of CV in the algorithm is important especially in areas where spatial variability becomes significant enough to make an impact on crop yield. Arnall et al. (2006) reported that when CVs from NDVI readings were greater than 20%, plant stands were likely <100 plants m^{-2} and as such considered poor. Further, Morris et al. (2005) noted that maximum yields could be achieved, even when N fertilization was delayed until mid-season. This was achieved when plot CVs were less than 18%.

The relationship established between NDVI measurements and biomass production was used to develop the technology that employs real-time optical sensing to predict yield potential of a crop and to variably apply N fertilizer based on the predicted yield (Stone et al., 1995 and 1996b). The optical sensor-based variable rate technology developed at Oklahoma State University can sense submeter-variability on-the-go and at the same time, variably apply N fertilizer based on plant needs. Various research programs have noted that spatially variable N fertilizer applications may reduce adverse environmental impacts and increase economic returns (Fiez et al., 1995). To effectively use this technology, sensing and treatment applications should be done at the finest resolution at which variation occurs, such that if management practices are employed at this resolution, positive impact on production and profit will be achieved. Some studies suggest that significant differences in soil and plant variables occur within a sampling distance as short as 0.3 m (Raun et al., 1998) and less than 1.96 m^2 (Solie et al., 1996). La Ruffa et al. (2001) demonstrated that in a high yielding environment of >2300 kg ha^{-1} grain, treating the variation at finer resolutions tended to increase NUE. Recent work by Raun et al. (2002) has shown that the present NUE was increased by 15% when N fertilization was based on optically sensed INSEY and a response index.

HYPOTHESIS AND OBJECTIVES

The hypothesis of this study was: 1) treating spatial variability at the finest resolution at which variation occurs will increase wheat grain yield and NUE. This study was conducted to determine at which scale spatial variability should be treated using the current in-season nitrogen fertilization optimization algorithm (NFOA), and to determine the benefits of treating variability at different resolutions.

MATERIALS AND METHODS

Field experiments were established on a Dale silt loam (fine-silty, mixed, superactive, thermic Pachic Haplustoll) in Chickasha and on a Tillman-Hollister clay loam (fine, mixed, thermic Pachic Arguistolls) in Tipton, Oklahoma in September and October 2003, respectively. In the 2005-06 cropping season, no trial was conducted at Tipton but an additional site was established at the Lake Carl Blackwell (LCB) Irrigated Research Station. The LCB site, west of Stillwater, OK, has a soil type classified as Pulaski fine sandy loam (coarse-loamy, mixed, superactive, nonacf, thermic Typic Ustifluvent). Before treatment application, composite soil samples were taken from the entire site at 0-15 cm depth, air-dried, processed and analyzed for pH, NH_4-N, NO_3-N, Mehlich-III extractable phosphorus (P) and exchangeable potassium (K). Results of the analyses are presented in Table 1.

Variable N rates were applied at three resolutions (0.84, 13.4 and 26.8 m^2), and two N application methods (preplant and midseason) at a fixed rate of 90 kg N ha^{-1}, and a check plot were laid-out in a completely randomized design (CRD) with three replications (Table 2). Field activities from 2003 to 2006 are detailed in Table 3. Each of the plots, measuring 3.7 m x 7.3 m, were divided into subplots using the resolutions mentioned (Figure 1). The resolutions were made by creating subplots with dimensions of 0.91 x 0.91 m, 3.7 x 3.7 m, and 3.7 x 7.3 m for 0.84, 13.4 and 26.8 m^2 whole plots, respectively.

Prior to midseason N applications for plots using different resolutions, NDVI readings and CVs from the NDVI readings were collected. Dates of sensing and midseason N application are summarized in Table 3. The GreenSeeker™ hand held optical sensor (NTech Industries, Inc.) was used to measure canopy reflectance and to collect NDVI readings based on a unit view of 0.6 x 0.01 m area held at a distance of 0.6 to 1.0 m from the crop canopy. The sensor measures red (671±10 nm) and near-infrared (NIR, 780±10nm) reflectance and calculates NDVI using the equation:

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}}$$

where: ρ_{NIR} = fraction of emitted NIR radiation returned from the sensed area

ρ_{RED} = fraction of emitted red radiation returned from the sensed area

The optical sensor was also used to obtain non-destructive measurement of CV from the NDVI readings for each subplot sensed.

The index INSEY was calculated by dividing NDVI by the number of days from planting to sensing where GDD>0. The NDVI-derived-INSEY is an index that predicts biomass produced on a daily basis and can be used to predict yield potential (YP_0) using the current algorithm for wheat (Raun et al., 2002). Yield potential when N is applied (YP_N) was determined by multiplying YP_0 with the response index (RI_{NDVI}). The RI_{NDVI} was determined by dividing the average NDVI from plots with the highest N applied by the NDVI average of check plots (0 N rate). The collected CV was used to adjust N rate recommendations. The N rate required to achieve YP_N for each subplot of resolutions tested was computed using the equation (Raun et al., 2005):

$$R_n = \frac{YP_0 N_g}{\varepsilon_n}(RI - 1)\left(\frac{(CV_{Cap} - CV_{Plot})}{(CV_{Cap} - CV_{Critical})}\right)$$

where:

R_n = N application rate, kg ha^{-1}

N_g = N content in grain, 0.0239 kg N kg^{-1}

ε_n = Expected N use efficiency

RI = Adjusted RI, $\left(\frac{NDVI_{N-Rich}}{NDVI_{Farmer}} \times 1.69\right) - 0.7$

CV_{Cap} = Coefficient of variation ceiling

$CV_{Critical}$ = Critical coefficient of variation value

CV_{Plot} = Coefficient of variation from the plot's NDVI readings

Table 4 presents the YP_0 equations and values of CV incorporated in the functional algorithm for midseason N rates determined for each cropping year. Nitrogen fertilizer was applied as urea ammonium nitrate solution (UAN, 28-0-0) on designated subplots of 0.84 m^2-resolution using a pulse modulated sprayer. For areas of lower resolutions (13.4 and 26.8 m^2), a backpack sprayer was used to apply midseason N.

The entire plot area was harvested with a self-propelled Massey Ferguson 8XP combine. Grain yield and percent moisture content were collected using a Harvest Master yield monitoring computer. Moisture content of the final grain yield data was adjusted to 12%. Grain subsamples were collected, oven dried at 70°C for 72 hours and processed to pass through a 106 um screen (140 mesh screen) for total N analysis using a Carlo Erba NA 1500 dry combustion analyzer (Schepers et al., 1989). Total N uptake was determined by multiplying percent grain N by grain yield. Nitrogen use efficiency was calculated by dividing the increase in grain N uptake due to N fertilization (N $Uptake_{FERILIZED}$ – N $Uptake_{CHECK}$) by the amount of N applied. Net return to N fertilizer was computed by subtracting the cost of total N applied from gross income (price of grain kg^{-1} multiplied by grain yield). Table 5 provides the prices of N fertilizer and wheat grain from 2004-2006 used in net return determination. Statistical analysis was performed using SAS for Windows (SAS, 2002). Analysis of variance (ANOVA), a procedure use to partition sources of variation, was conducted using SAS General Linear Model (GLM) Procedure to determine if there were differences in mean grain yield, grain N uptake, NUE and net return to N fertilizer due to treatment.

RESULTS

Total Nitrogen Applied

Table 6 summarizes the average total N fertilizer applied for each treatment across sites and years. The average NDVI and CV by site year are also reported. The midseason NFOA-based N fertilizer rates were consistently lower than the fixed rate (90 kg ha^{-1}) which averaged only 57, 45 and 60 kg N ha^{-1} for Chickasha, Tipton and LCB sites, respectively. The N requirements projected by the algorithm tended to be higher when average NDVI readings were higher as exemplified at Chickasha in 2005. At this site, the NFOA-projected N rates of 80, 82 and 90 kg N ha^{-1}, almost equaled the 90 kg N ha^{-1} fixed rate applied. The Tipton site in 2004 had similar average NDVI readings at 0.702, but the algorithm prescribed an average of only 35 kg N ha^{-1}. This was attributed to a higher average CV and wider CV range collected in this particular site and year. The difference in crop stand expressed by the higher CVs was explained by the higher seeding rate at Chickasha in 2005 (134 kg ha^{-1}) compared with Tipton's 80 kg ha^{-1} for 2004 and 2005 (Table 3).

The NFOA at the highest resolution (0.84 m^2) consistently prescribed the lowest N rates except at Chickasha in 2005 where the average CV reading was only 5.2%, the lowest value collected. The difference among NFOA-based N rates of the three resolutions was more pronounced in cropping seasons where the average CV was high. This observation was exemplified at Tipton in 2005 where the spatial variability treated at 0.84m^2 using the NFOA had the lowest N applied at only 39 kg ha^{-1} compared with the lower resolutions' (13.4 and 26.8 m^2) at 62 and 61 kg ha^{-1}.

Grain Yield

Grain yield means, RI_{NDVI} and $RI_{HARVEST}$ are presented by treatment, site and year in Table 7. Also, the standard error of the difference (SED) between two means is reported by year for every site. There were significant differences in mean grain yield at all sites and years except Chickasha in 2006. The highest yield was 4237 kg ha^{-1} obtained at Tipton in 2004, the same site year where a high average NDVI reading of 0.702 was reported (Table 6).

Winter wheat planted at Tipton in 2005 was the most responsive to N fertilizer applications. This was reflected in the RI_{NDVI} (2.11) and $RI_{HARVEST}$ (2.06) values recorded. In 2004 at Chickasha, a high RI_{NDVI} of 1.95 was found but the corresponding $RI_{HARVEST}$ was only 1.46. The two lowest yielding site years attained only 1629 and 2030 kg of grain ha^{-1} (Table 7). Average NDVI readings presented in Table 6 were also the lowest at these two sites. The average NDVI reading at Chickasha was only 0.283 while at Tipton in 2005 it was 0.373.

The highest grain yields were obtained from plots with a fixed N rate at 90 kg N ha^{-1} midseason excluding LCB and Chickasha in 2006 where even the check plot produced higher grain yields. When fixed rates were preplant applied, increases in yields were lower compared to when N was applied midseason. In some site years, plots that were applied with NFOA-based N rates produced higher grain yields. On average at Chickasha, NFOA-based N rate treatments achieved 100 kg ha^{-1} more grain yield than 90 kg N ha^{-1} preplant, and >300 kg ha^{-1} at LCB. These yield differences were small but plots employing NFOA-based N rate treatments received 40% less N when compared to the 90 kg N ha^{-1} fixed rate. One-time, large preplant N fertilizer applications are not beneficial to crops since at the early growth stage the demand for N is very low. Doerge et al. (1991) documented that N flux (kg N ha^{-1} day^{-1}) increases to a maximum during the jointing stage. The start of stem elongation, Feekes growth stage 6 (Large, 1954) or Zadoks 31 (Zadoks et al., 1974), is identified to be the start of the rapid N uptake by the wheat crop. The amount of N that is taken up by the crop during the early stages of growth can potentially be lost even before the crop reaches the maximum vegetation production where the demand for N peaks. Only modest amounts of N applied preplant or at planting are important for early crop establishment.

The increase in grain yields of plots with NFOA-based N rates at different resolutions varied. There were site years where the NFOA-based N rates exceeded the grain produced by plots that received the 90 kg N ha^{-1} fixed N rate. In 2006 at Chickasha, grain yield of the NFOA-based N rate of 45 kg N ha^{-1} was higher than the 90 kg ha^{-1} fixed rate (both preplant and midseason applied). However, this yield difference (3886 versus 3834 kg ha^{-1}) was not significant (SED = 184). In 2006 at LCB, grain yield differences between fixed and NFOA-based N rates treated plots was significant (SED = 173) and from plots treated at the highest resolution of 0.84 m^2. While there were site years that the NFOA-based N rates did not achieve grain yields as high as the fixed rate treated plots, it is important to take note that these variable rates never exceeded the 90 kg N ha^{-1} fixed rate. Moreover, on average, the NFOA-based N rates prescribed almost half (40% less) of the fixed rate.

Grain Nitrogen Uptake

Table 8 presents grain N uptake by treatment, site and year. There were significant differences in mean grain N uptake across sites and years excluding 2006 at Chickasha ($Pr<0.05$). For the check plot's grain N uptake, the lowest value of 19 kg ha^{-1} was obtained in 2005 at Tipton. This was followed by 26 kg N ha^{-1} at Chickasha in 2004. These two lowest grain N uptake values represented the same site years where the two highest RI_{NDVI} values were obtained (Table 7). Winter wheat in these two site years was very responsive to N fertilizer application. However, on average, these two site years were also reported to have the lowest grain yield (Table 7) and N uptake (Table 8). The highest grain N uptake among treatments was achieved in plots where N was applied midseason at a 90 kg ha^{-1} fixed rate across sites and years excluding 2006 at Chickasha. The difference in N uptake between NFOA- and fixed rate treatments was not proportionate to the difference in the N rates applied. While the NFOA-based N rate recommendations were 40% less than the 90 kg N ha^{-1} fixed rate, grain N uptake differences at Chickasha, Tipton and LCB were 8, 23 and 12%, respectively, and less than the fixed rates'.

On average, midseason NFOA-based N rate treatments achieved only about 85% of the grain N uptake of the 90 kg N ha^{-1} fixed rate treatment applied midseason. No pronounced trend was observed when comparing the NFOA-based N rate treatments at different resolutions. On average at Chickasha, grain N uptake values were very similar. At 0.84, 13.4 and 26.8 m^2 resolutions, average grain N uptake values were 66, 69 and 67 kg ha^{-1}, respectively. The low-resolution 26.8 m^2 achieved the highest grain N uptake of 54 and 91 kg ha^{-1} for Tipton and LCB sites, respectively. This was the optimum resolution identified at which the NFOA-based N rates applied resulted in maximum N uptake by the crop.

Nitrogen Use Efficiency

Nitrogen use efficiency was computed by taking the difference in N uptake between the N fertilized plot and the check, and dividing by the rate of N applied. Table 9 summarizes NUE results by treatment, site and year. The ANOVA analysis showed that while there were differences in NUE among treatments, these were not significant ($Pr<0.05$). This outcome was consistent across sites and years. It is noteworthy that one-time preplant application of 90 kg N ha^{-1} resulted in the lowest NUE among treatments which also occurred consistently across sites and years. Note that this is similar to the observation in grain yield response that was reported earlier. The lowest NUE was 14% at Chickasha in 2006 coming from the plot that received 90 kg N ha^{-1} preplant. The highest was 56% obtained in 2004 at Tipton from plots treated with variable N rates prescribed by NFOA at 13.4 m^2 resolution.

On average by site, midseason NFOA-based N rate recommendations resulted in higher NUE when compared with the fixed N rate applications. At Chickasha, the fixed rate plots averaged only 26% while the NFOA-based plots was 35%. At Tipton, the fixed N plot recorded only 32% compared to 41% for NFOA-based treatment. The 90 kg N ha^{-1} fixed rate treatment achieved 40% NUE while the NFOA-based treatments were 46% at LCB. On average, the NFOA approach resulted in 41% NUE compared with 33% of the 90 kg N ha^{-1} fixed rate applied midseason. The highest NUE values achieved among the midseason NFOA-base plots were 39 and 44% for Chickasha and Tipton sites, respectively both treated at 13.4 m^2 resolutions. At LCB, plots treated at the lowest resolution of 26.8 m^2 obtained the highest NUE value of 54%.

Net Return to Nitrogen Fertilizer

Net return was computed by subtracting the cost of N fertilizer used from the price of grain produced. Table 10 summarizes the net return of wheat production in response to N fertilizer applied at fixed and NFOA-based N rates by treatment, site and year. Analysis of variance showed that mean net returns were significantly different ($Pr<0.05$) at Chickasha in 2005, at Tipton for both years (2004 and 2005) and at LCB. At Chickasha, the highest net return among treatments was consistently achieved by at least one of the NFOA-based N rate treatments. The highest return was \$ 460 ha^{-1} from plots with midseason NFOA-based N rates treated at 13.4 m^2 resolution. Similarly, at LCB, \$ 642 ha^{-1} net return was achieved from mid-season-NFOA-based N rate recommendation at the 26.8 m^2 resolution. However, at Tipton, there was no economic benefit obtained when midseason NFOA-based rate recommendations were used. On average at Tipton, midseason NFOA-based N rate recommendations' net return were comparable with the 90 kg N ha^{-1} fixed rate's applied preplant. However, this was not the case when compared with fixed rates applied midseason. Midseason application of 90 kg N ha^{-1} resulted in significantly higher net returns of \$ 524 and 256 ha^{-1} in 2004 and 2005, respectively. Savings from reduced fertilizer use when using the NFOA-based approach calculated by subtracting the net return of 90 kg N ha^{-1} fixed rate treatment applied midseason or preplant from the highest net return of the NFOA-based N rate treatments. Excluding Tipton site, savings on cost of N fertilizer used ranged from \$ 5-101 ha^{-1} when compared with 90 kg N ha^{-1} rate applied midseason. This can be attributed to the large reduction in the amounts of N applied reported in Table 6. When the NFOA approach was compared to fixed rates preplant, with the exception of Tipton site, savings obtained ranged from \$ 32-101 ha^{-1}.

When comparing net returns of the NFOA-based N rate treatments at different resolutions, treating spatial variability at 13.4 m^2 resolution had the highest net return. Using NFOA in prescribing N rates at the finest resolution of 0.84 m^2 did not exhibit any economic benefit (Table 10). Trends of net returns for different resolutions and prices of N fertilizer at $ 0.08 and 0.18 kg^{-1} of wheat grain are presented in Figure 2 and 3, respectively. Figure 2 shows that at $ 0.08 kg^{-1} of wheat grain, the lowest wheat grain price reported in the past 10 years (USDA NASS, 2007), treating spatial variability at 0.84 m^2 exceeded net returns of the lower resolutions (13.4 and 26.8 m^2) only when the price of N fertilizer was at least $ 0.60 kg N^{-1}. However, when wheat grain price was $ 0.18 kg^{-1}, highest reported in the past 10 years (USDA NASS, 2007), there was a consistent decreasing trend of net returns with increasing resolution for the three prices ($ 0.40, 0.60 and 0.80 kg N^{-1}) of N fertilizer evaluated.

DISCUSSION

The components of the NFOA which include prediction of yield potential, response index and coefficient of variation can be determined in-season. This approach makes N rate recommendations tailored for the current crop and are not based on historical information. Each of these components provide an important function so that the algorithm can precisely estimate N application based on N demand at the projected yield potential while taking into account field spatial variability and the seasonally dependent crop responsiveness to applied N. The NDVI normalized by GDD is used to predict yield potential using the equation presented in Table 4 and that is annually updated. The coefficient values from recent years' YP_0 equations have been relatively stable. The recent YP_0 equation for 2007 is YP_0 = 590*exp(INSEY*258.2) (http://www.nue.okstate.edu/Yield_Potential.htm). The strength of this YP_0 equation is limited by significant changes in growth conditions that occur after sensing which can either adversely or favorably influence crop yield potential. Otherwise, the YP_0 equation can be used to obtain reasonable estimates of actual grain yield. The closest projection was at Tipton in 2005 where predicted yield potential was 1616 kg $ha^{-1}$and the actual yield obtained at harvest was 1250 kg ha^{-1} (Table 7). However at Chickasha in 2006, the predicted yield potential was 1501 kg ha^{-1} which was only 58% of the actual yield.

The NFOA projected N fertilizer rates did not exceed the 90 kg N ha^{-1} fixed rate used in any of the trials (Table 2). The only time that NFOA-based N rates equalled the fixed rate was in 2005 at Chickasha. This was also the site year where one of the NFOA's N rate recommendations recorded the highest yield among treatments. As shown in Table 6, this site year recorded the highest average NDVI reading (0.705), the lowest average CV (5.2%) and a narrow CV range (12.9%). The N rate recommendations prescribed at Tipton in 2004 were remarkably lower even though the average NDVI reading (0.702) was equally high as at Chickasha in 2005. The relatively lower RI_{NDVI} compared with Chickasha's caused a reduction of the N rate recommendations prescribed by NFOA. Moreover, this site year recorded a relatively higher average CV of 16.7% and a number of subplots obtaining CV values as high as 37.9%. The higher CVs likely caused further reduction of the final N rate recommendations. This is the advantage of the present algorithm such that when variation in the field becomes pronounced (high CVs), N rate recommendations decline. The integration of CV, an estimate of variation in plant-stand densities, will assist in identifying areas in the field where N application should be reduced. This makes the current N-fertilization algorithm (Raun et al., 2005) vastly different to the algorithm used by Raun et al. (2002). The capability of the algorithm to project what the crop needs has resulted in increased NUE and net return. The large savings in the amount of N fertilizer prescribed by NFOA outweighed the large increases in grain yield and N uptake incurred by applying 90 kg N ha^{-1} midseason when computing NUE and net return. On average by site, at least two of the NFOA-based treatments consistently obtained higher NUE compared with the fixed rate (Table 9). Statistically, the increase in NUE was not significant ($Pr<0.05$), however, considering economic and environmental perspectives, it can make a difference. A 1% increase in NUE worldwide would save $ 234,658,462 in fertilizer cost and would mean 489,892 metric tons of N fertilizer saved and that would not adversely contaminate our environment (Raun and Johnson, 1999).

The economic analysis of this trial was highlighted by presenting the net returns and savings incurred when the NFOA approach was used to determine N rate requirement using the 90 kg N ha^{-1} fixed rate treatment applied midseason as a reference. Four out of six site years had at least one of the NFOA treatments that exceeded the net returns of the fixed rates. The net returns of as much as $ 40 and $ 27 ha^{-1} were saved at Chickasha and LCB sites, respectively. As presented earlier, grain yield of NFOA-based N rate plots were relatively lower than that of the fixed rate applied midseason which in turn resulted in relatively lower net return. However, the significant reduction in the amount of fertilizer applied lowered the cost of N fertilizer input resulting in a higher net return. In addition to considerable reduction in the cost of N fertilizer used, grain yield of the NFOA-based approach in some site years exceeded the grain yield of the preplant 90 kg N ha^{-1} fixed rate. This demonstrates that the NFOA approach is very promising in terms of improving producer's income.

The results presented above and the previous study by Raun et al. (2002) demonstrated that higher NUE and net return can be achieved when N rate recommendations were based on N demand encumbered within predicted yield potential. However, the optimum resolution to treat spatial variability needs to be determined to maximize the benefit when using NFOA to project crop N rate requirements. This is particularly important for variable rate technology where wheat fields are sensed on-the-go while concurrently treating the crop based on needs. When spatial variability was treated at the highest resolution, the only benefit obtained was a marginal increase in NUE, 36% compared with the 31 and 34% of the 13.4 and 26.8 m^2 resolutions, respectively. This was only true in one site year (Tipton, 2005) where the average CV of the plots exceeded the critical CV (20%) used in the algorithm. On average by site, treating spatial variability using the NFOA at 13.4 m^2 resulted in the highest NUE values among the treatments, reported at 56 and 44% for Chickasha and Tipton sites, respectively. Further, the net returns (Table 10) for this resolution for both sites were recorded to be the highest among the three resolutions tested. At LCB, the optimum resolution where the highest NUE and net return could be achieved was identified to be at 26.8 m^2. Net returns for different prices of N fertilizer at fixed grain price of $ 0.18 kg^{-1} consistently decreased with increasing resolution (Figure 3). However, when price of grain was at the lower end ($ 0.08 kg^{-1}) and the price of N fertilizer was at the higher end (at least $ 0.60 kg N^{-1}), treating spatial variability at 0.84 m^2 exceeded the net returns of the lower resolutions (Figure 2). These results also suggest that when crop stand has a CV value more than the 20% critical CV in the algorithm (exhibited in one site year only), treating the spatial variability at 0.84 m^2 (finest resolution in this trial) would result in a higher NUE. However, this requires further verification as there existed only a marginal difference (2%) when compared with the NUE achieved at 26.8 m^2 resolution.

CONCLUSION

Based on the results reported, when an NFOA approach was used to determine midseason N rate requirements, treating spatial variability at least at 13.4 m^2 resulted in increased NUE and net return. Treating spatial variability at 0.84 m^2 resulted in a positive impact on net return and NUE only: a) when the average CV, an estimate of crop stand, was greater than 20%, and b) when the price of N fertilizer was at least \$ 0.60 kg N^{-1} provided that the price of wheat grain was \$ 0.08 kg^{-1}. Further research should be conducted to verify these results as there existed only a marginal difference in NUE when compared with the lower resolutions. Mathematical adjustment has to be made to refine the current algorithm in order to affect an increase in NUE and net return.

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Table 1. Soil chemical properties determined prior to experiment from initial soil samples (0-15 cm) at three locations, Oklahoma.

Site	pH	mg kg^{-1}			
		NH_4-N	NO_3-N	P	K
Chickasha	6.3	7.2	30	46	230
Tipton	7.0	7.7	1	12	21
LCB	6.4	9.6	13	15	150

pH – 1:1 soil:water; K and P – Mehlich III; NH_4-N and NO_3-N – 2 M KCl.

Table 2. Treatment structure and description for resolution trials at three sites in Oklahoma, 2004-2006.

No.	Treatment Code	N Rate, kg ha-^{1}	Method	Resolution, m^2
1	Check	0	check	-
2	Preplant-90	90	preplant	-
3	Mid-90	90	topdress	-
4	Mid-NFOA-0.84m^2	¶	midseason NFOA	0.84
5	Mid-NFOA-13.4m^2	¶	midseason NFOA	13.4
6	Mid-NFOA-26.8m^2	¶	midseason NFOA	26.8

¶ Rates were determined based on Nitrogen Fertilization Optimization Algorithm (NFOA).

Table 3. Field activities for all sites and years, 2003-2006.

Site	Cropping Season	Variety	Seeding Rate kg ha^{-1}	Date‡			
				Planting	Sensing¶	Topdress† Application	Harvest
Chickasha	2003-04	OK102	90	09-30-03	03-17-04	03-17-04	06-03-04
	2004-05	2174	134	10-05-04	03-07-05	03-07-05	06-21-05
	2005-06	Endurance	90	10-05-05	03-27-06	03-27-06	06-09-06
Tipton	2003-04	2158	80	11-07-03	03-11-04	03-16-04	05-27-04
	2004-05	Cutter	80	09-30-04	02-28-05	03-03-05	06-14-05
LCB§	2005-06	Fannin	97	10-13-05	03-13-06	03-14-06	06-15-06

§ Lake Carl Blackwell
‡ Date in month-day-year.
† Topdress application date for treatments 3, 4, 5 and 6.
¶ Sensing accomplished at Feekes growth stage 5.

Table 4. Yield potential equations, critical and maximum values of coefficient of variation, and the number of days from planting to sensing that were used to compute midseason nitrogen rates at three locations in Oklahoma, 2004-2006.

Year	YP_0 Equation	Coefficients of Variation, %		Number of Days‡		
		Critical	Maximum	Chickasha	Tipton	LCB†
2004	YP_0 = 359*exp(INSEY*324.4)	25	100	111	127	-
2005	YP_0 = 522*exp(INSEY*274.7)	20	60	112	119	-
2006	YP_0 = 532*exp(INSEY*270.1)	20	60	120	-	106

YP_0 = yield potential equation

INSEY = in-season estimated yield computed by dividing NDVI readings at Feekes growth stage 5 by the number of positive growing degree days $\left(GDD = \frac{T_{max} + T_{min}}{2} - 4.4°C\right)$ from planting to sensing

‡ Number of days from planting to sensing where GDD>0.

† Lake Carl Blackwell

Table 5. Prices of nitrogen fertilizer and wheat grain used for net return computation, 2004-2006.

Year	Grain Price†	Price N Fertilizer‡
	$ kg^{-1}	$ kg N^{-1}
2004	0.12	0.59
2005	0.12	0.71
2006	0.18	0.75

† All winter wheat grain, Source: USDA, NASS.

‡ Estimated U.S. Farm level fertilizer prices, Source: US Department of Energy.

Table 6. Total nitrogen fertilizer applied at fixed and midseason NFOA-based rates at different resolutions at three locations in Oklahoma, 2004-2006.

Treatment Code¶	Chickasha				Tipton			LCB
	2004	2005	2006	Avg.	2004	2005	Avg.	2006
	Total N Applied, kg ha^{-1}							
Check	0	0	0	0	0	0	0	0
Preplant-90	90	90	90	90	90	90	90	90
Mid-90	90	90	90	90	90	90	90	90
Mid-NFOA-0.84m^2	41	90	36	56	34	39	36	53
Mid-NFOA-13.4m^2	50	80	43	58	37	62	50	62
Mid-NFOA-26.8m^2	47	82	45	58	35	61	48	66
Average NDVI§	0.283	0.705	0.458	-	0.702	0.373	-	0.539
Average CV	12.9	5.2	13.0	-	16.7	23.6	-	13.1
Maximum CV	20.9	14.9	28.4	-	37.9	37.9	-	26.8
Minimum CV	7.1	2.0	4.2	-	8.9	11.0	-	3.7

¶ Refer to Table 2 for treatments' full description.

§ Average NDVI of midseason NFOA-based N treated plots.

CV = Coefficient of variation, %, from NDVI readings of midseason NFOA-based N treated plots

Table 7. Wheat grain yield response to applied nitrogen at fixed and midseason NFOA-based rates at three locations in Oklahoma, 2004-2006.

Treatment Code¶	Chickasha				Tipton			LCB
	2004	2005	2006	Avg.	2004	2005	Avg.	2006
	Grain Yield, kg ha^{-1}							
Check	1216	2999	2583	2266	3393	1250	2322	2435
Preplant-90	1697	3628	3705	3010	4689	2081	3385	2308
Mid-90	1781	4186	3834	3267	4726	2578	3652	2308
Mid-NFOA-0.84m^2	1628	4179	3330	3046	4253	1945	3099	2637
Mid-NFOA-13.4m^2	1708	4169	3453	3110	4267	2130	3198	2676
Mid-NFOA-26.8m^2	1746	3813	3886	3148	4092	2194	3143	2692
Pr>F	0.0384	0.0005	0.4719	-	0.0002	0.0001	-	0.0029
Adj. RI_{NDVI}§	1.95	1.42	1.36	-	1.24	2.11	-	1.38
$RI_{HARVEST}$†	1.46	1.40	1.48	-	1.39	2.06	-	1.0
Yield Avg.‡	1629	3829	3465	-	4237	2030	-	2509
YP_0	818	2676	1501	-	1994	1316	-	2130
SED	133	144	184	-	135	77	-	173

¶ Refer to Table 2 for treatments' full description.
§ Adjusted in-season response index, determined by dividing average Normalized Difference Vegetation Index (NDVI) at Feekes growth stage 5 from Preplant-90 by the Check. Adjustment made using the equation (RI_{NDVI}x1.69) - 0.7.
† Response index at harvest, determined by dividing the grain yield of highest N fertilized plots by the yield of the Check plot.
‡ Average yield of all treatments by site year in kg ha^{-1}.
YP_0 = predicted yield potential of the check plot in kg ha^{-1}
SED = Standard error of the difference between two equally replicated means

Table 8. Grain nitrogen uptake response to applied nitrogen at fixed and midseason NFOA-based rates at different resolutions at three locations in Oklahoma, 2004-2006.

Treatment Code¶	Chickasha				Tipton			LCB
	2004	2005	2006	Avg.	2004	2005	Avg.	2006
	Grain N Uptake‡, kg ha^{-1}							
Check	26	58	55	46	51	19	35	54
Preplant-90	45	83	64	64	84	35	59	86
Mid-90	50	99	70	73	87	48	68	94
Mid-NFOA-0.84m^2	36	94	67	66	65	33	49	76
Mid-NFOA-13.4m^2	41	95	72	69	70	39	54	82
Mid-NFOA-26.8m^2	40	88	72	67	68	40	54	91
Pr>F	0.0008	0.0001	0.0621	-	0.0002	0.0001	-	0.0087
SED	2.6	3.9	3.9	-	3.8	1.6	-	6.0

¶ Refer to Table 2 for treatments' full description.
‡ Grain yield multiplied by the percent N in grain.
SED = Standard error of the difference between two equally replicated means

Table 9. Nitrogen use efficiency in response to applied nitrogen at fixed and midseason NFOA-based rates at different resolutions at three locations in Oklahoma, 2004-2006.

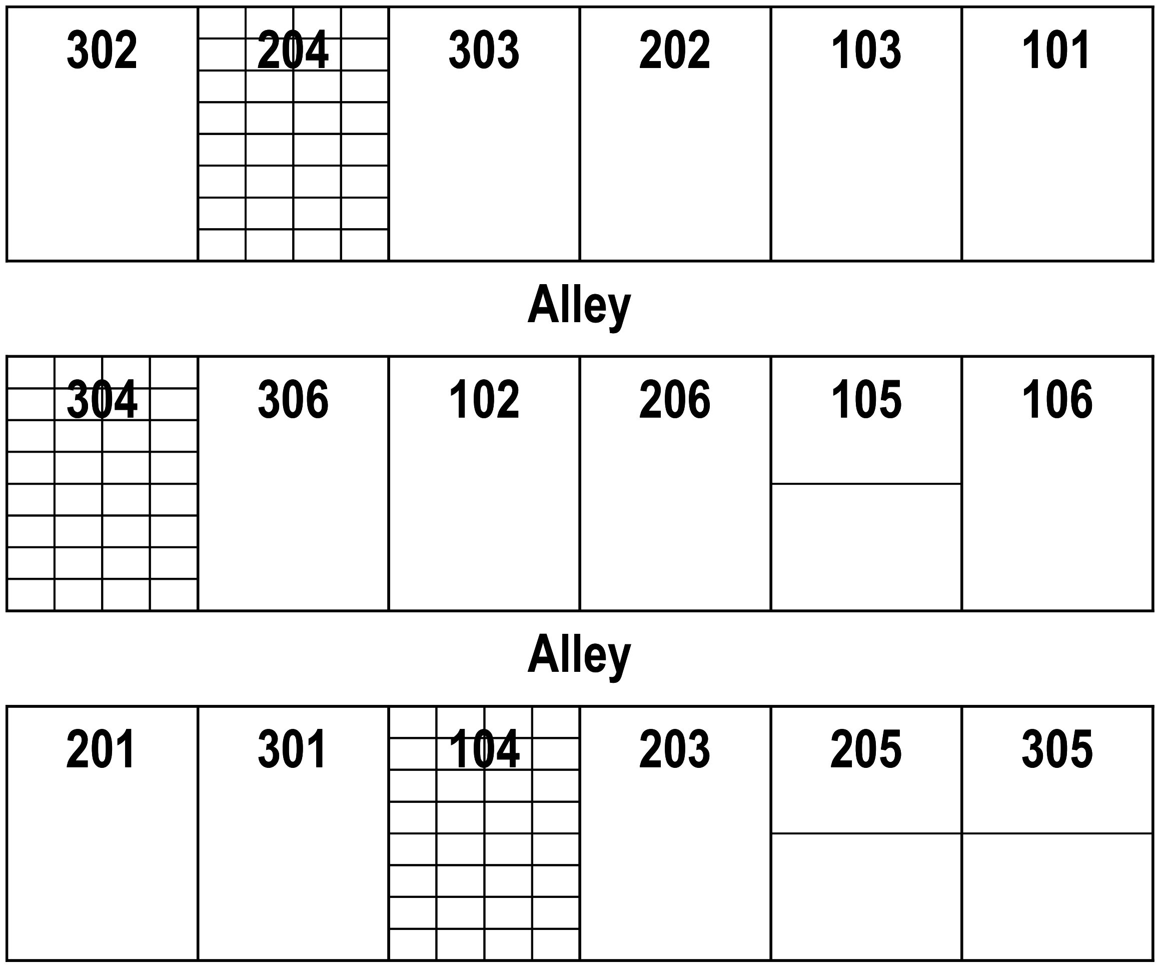
Treatment Code¶	Chickasha				Tipton			LCB
	2004	2005	2006	Avg.	2004	2005	Avg.	2006
	Nitrogen Use Efficiency†, %							
Check	-	-	-	-	-	-	-	-
Preplant-90	21	28	14	21	37	17	27	35
Mid-90	27	45	17	30	41	32	36	44
Mid-NFOA-0.84m^2	26	40	32	32	43	36	39	40
Mid-NFOA-13.4m^2	30	47	39	39	56	31	44	44
Mid-NFOA-26.8m^2	31	37	38	35	49	34	41	54
Pr>F	0.5784	0.4819	0.2585	-	0.8675	0.0696	-	0.4818
Average NUE‡	27	39	28	-	45	30	-	43
SED	4.5	7.9	9.2	-	13.6	4.0	-	6.6

¶ Refer to Table 2 for treatments' full description.
† Estimated by subtracting the grain N uptake of the check plot from the fertilized plot, divided by the N rate applied.
‡ Average nitrogen use efficiency of all the treatments by site year.
SED = Standard error of the difference between two equally replicated means

Table 10. Net return to nitrogen fertilizer for resolution trials at three locations in Oklahoma, 2004-2006.

Treatment Code¶	Chickasha				Tipton			LCB
	2004	2005	2006	Avg.	2004	2005	Avg.	2006
	Net return§, \$ ha^{-1}							
Check	148	372	433	318	414	155	285	460
Preplant-90	154	386	344	295	519	194	357	592
Mid-90	164	455	344	321	524	256	390	615
Mid-NFOA-0.84m^2	175	454	443	357	499	213	356	553
Mid-NFOA-13.4m^2	179	460	444	361	499	220	359	568
Mid-NFOA-26.8m^2	186	415	445	348	479	229	354	642
Pr>F	0.4096	0.0144	0.1004	-	0.0055	0.0002	-	0.0136
SED	13.75	17.99	32.78	-	16.48	9.58	-	27.46

¶ Refer to Table 2 for treatments' full description.
SED = Standard error of the difference between two equally replicated means
§ Grain price kg^{-1} multiplied by yield and then subtracted by cost of total N applied. Prices of fertilizer and wheat grain are reported in Table 5.



Plot size: 3.7 m x 7.3 m
Alley: 3.0 m
Subplot size: Treatment 4 (0.84 m^2) – 0.9 m x 0.9 m
Treatment 5 (13.4 m^2) – 3.7 m x 3.7 m
Treatment 6 (26.8 m^2) – 3.7 m x 3.7 m

Figure 1. A plot plan sample for resolution trials, Oklahoma, 2004-2006.

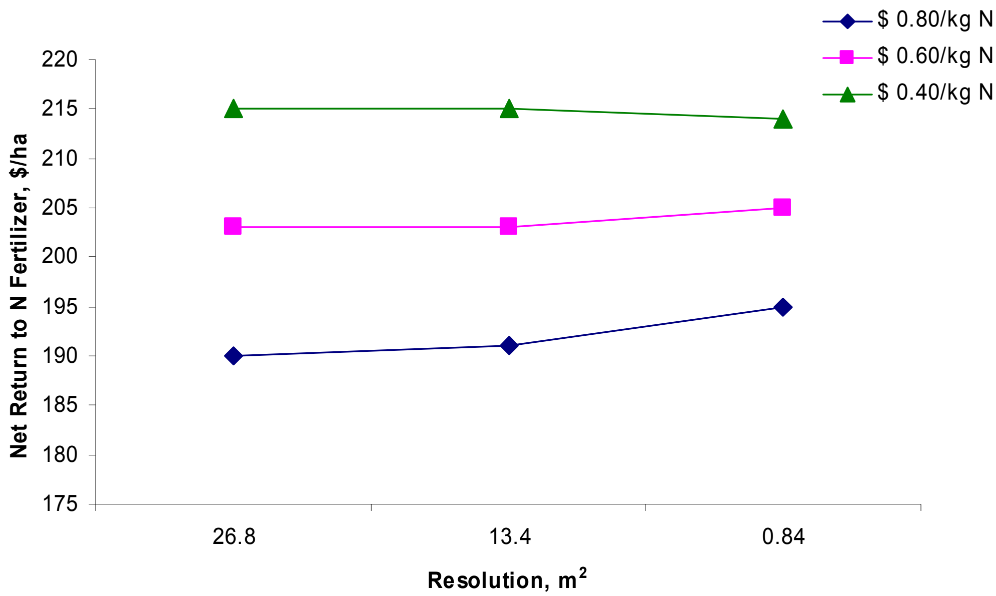


Figure 2. Net returns for different resolutions and prices of nitrogen fertilizer at a fixed wheat grain price of $ 0.08 kg^{-1}.

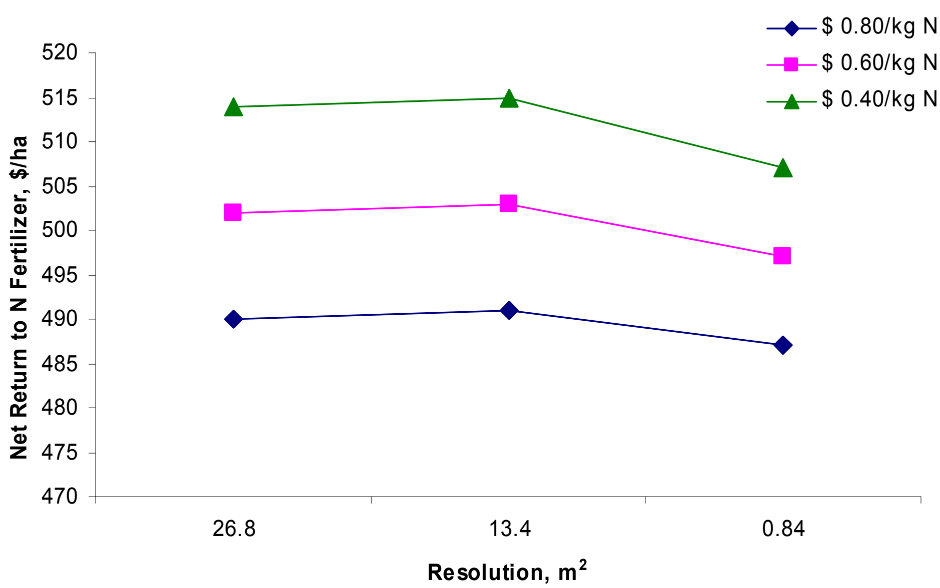


Figure 3. Net returns for different resolutions and prices of nitrogen fertilizer at a fixed wheat grain price of $ 0.18 kg^{-1}.

ADJUSTING MIDSEASON NITROGEN RATE USING A SENSOR-BASED OPTIMIZATION ALGORITHM TO INCREASE USE EFFICIENCY IN CORN (*Zea mays* L.)

ABSTRACT

Successful use of sensor based nitrogen (N) rate recommendations has resulted in an increase in N use efficiency (NUE) in winter wheat production. Due to increasing N fertilizer costs, development of a functional algorithm to optimize N fertilization in corn production is also essential. This study was conducted to formulate an in-season N fertilization optimization algorithm (NFOA) to estimate midseason N rates that maximize corn growth and minimize inputs. In addition, the optimum resolution to treat spatial variability for NFOA-based sidedress N rates was determined. Midseason N rate recommendations were computed using predicted yield potential (YP_0), crop N response estimated by the response index (RI), and coefficient of variation (CV), all derived from the Normalized Difference Vegetation Index (NDVI) readings. The experiment was established at three locations in 2004 near Stillwater, Oklahoma consisting of 13 treatments arranged in a randomized complete block design (RCBD) with three replications. Treatments included: a check plot; a 134 kg N ha^{-1} fixed rate applied in split, preplant- and sidedress-only; a 67 kg N ha^{-1} fixed rate applied preplant- and sidedress-only; three NFOA-based midseason N rates (RICV-NFOA, RI-NFOA, flat RICV-NFOA) with (67 kg N ha^{-1}) and without preplant N; and two resolutions (0.34 and 2.32 m^2) tested for RICV-NFOA only. The flat RICV-NFOA-based midseason N rates were determined using the variable rate average from the RICV-NFOA. With 67 kg N ha^{-1} preplant application, midseason-RI-NFOA-based N rates improved NUE to 64% compared with 56% of the 134 kg N ha^{-1} fixed rate split applied. The RI-NFOA was better than RICV-NFOA in improving grain yield, NUE and net return in high yielding site years but not in low yielding site years. Without preplant N in low yielding site years, the RICV-NFOA had higher NUE value (59% versus 43%) and net return ($ 475 versus $ 401 ha^{-1}) compared with RI-

NFOA's. There was no benefit on NUE and net returns when spatial variability was treated at 0.34 m^2 using RICV-NFOA. In general, the use of midseason sensor-based predictions of YP_0 and RI_{NDVI} provided accurate N rate recommendations when compared to flat rates.

INTRODUCTION

Traditional Nitrogen Management in Corn Production

Corn is grown throughout the world and is one of the most important cereal crops for human consumption. In 2003, the United States grew 38% or 257 million metric tons of the world's corn production (US Grain Council, 2003). Traditionally, farmers treat each field uniformly and base their N management decisions on yield goals which can be determined from a recent 5-year crop yield average plus an increase of 10-30% to assure non-limiting supply of N (Johnson, 1991; Dahnke et al., 1988). Johnson et al. (1997) used both yield goal and soil nitrate (NO_3-N) levels as basis for N rate recommendations. They came up with a recommendation guideline for wheat (*Triticum aestivum* L.): 33 kg N ha^{-1} should be applied for every 1 Mg of yield goal. For corn, Schmitt et al. (1998) reported that 20 kg N ha^{-1} is required for every 1 Mg of yield goal. The soil NO_3-N level present in the soil should be subtracted when using these recommendation guidelines. Since N fertilizer requirement is temporally dependent (Baethgen and Alley, 1989) and may vary among and within fields (Ferguson et al., 2002), uniform application of N fertilizer is not an efficient practice (Mulla and Bhatti, 1997; Khosla and Alley, 1999; Khosla et al., 2002; Hornung et al., 2003; Koch et al., 2004).

One-time large application of N fertilizer preplant leads to losses or immobilization before plant uptake, significantly affecting NUE (Welch et al., 1996; Olson and Shallow, 1984; Lutcher and Mahler, 1988; Fowler and Brydon, 1989; Wuest and Cassman, 1992). Nitrogen fertilizer can be lost from the soil-plant system through denitrification (Burford and Bremner, 1975; Olson et al., 1979, Burkart and James, 1999), runoff (Gascho et al., 1998; Burkart and James, 1999), leaching (Goss and Goorahoo, 1995) and gaseous plant N loss, predominantly as NH_3 (Francis et al., 1993).

Traditional N management systems may result in reduced economic returns, poor NUE, and increased environmental and health risks (Huggins and Pan, 1993; Raun et al., 2002). The presence of excess N fertilizer in the soil-plant system has been reported to be the main source of NO_3-N accumulation in the soil (Vyn et al., 1999). Spruill et al. (1996) reported that N fertilization in agricultural areas has been cited as the cause of high NO_3-N concentration in perched groundwater. Within the Midwest Corn Belt, NO_3-N concentrations in surface waters are often >10 mg L^{-1}, the U.S. Environmental Protection Agency's maximum contaminant level (MCL) for drinking water (Jaynes et al., 1999; Mitchell et al., 2000). As a result, cost of water treatment in some cities has increased due to installation of denitrification systems to remove NO_3-N from drinking water (Dinnes et al., 2002). The Mississippi River watershed serves as drainage of NO_3-N-contaminated surface water that was leached and/or washed from corn-soybean production areas in the Midwest (David et al., 1997; Goolsby et al., 1999; Jaynes et al., 1999). This in turn was identified as the primary source of NO_3-N in the Gulf (Goolsby et al., 1999) and as a leading cause of hypoxia in the northern Gulf of Mexico (Rabalais et al., 1996).

Management Practices to Improve Nitrogen Use Efficiency

Practices employed to improve NUE include proper timing of N applications, avoiding excess application of N fertilizer (Kanampiu et al., 1997) and multiple inputs of N in small amounts, all of these reducing the potential loss of unused N in the soil system. Fageria and Baligar (2005) reported that besides using appropriate N forms, placement, and timing, the use of diagnostic tools and models that can estimate plant N requirement on a need basis can improve N management decision. Split N fertilizer application is important to maximize crop utilization of applied N throughout the growing season (Boman et al., 1995). Cassman et al. (1992) showed that yield and protein content of wheat was improved when multiple application of N before planting and during the growing season was adopted. Late-season N deficiency detection could allow farmers the option of adjusting N rates according to crop growth, and that could reduce potential N losses due to leaching and denitrification. However, the environmental factors influencing N cycling complicate the present N status monitoring of crops (Westerman et al., 1994). Below et al. (1992) noted that the lack of a relationship between responsiveness to fertilizer N and late-spring soil NO_3-N tests was partly due to a variable proportion of the soil N as NH_4-N. Traditionally, corn N requirements have been based on soil testing (Magdoff, 1991), tissue N concentration (Tyner and Webb, 1946), and chlorophyll concentration or leaf greenness (Varvel et al., 1997). Blackmer and Schepers (1996) reported that these methods can be expensive, time consuming, require multiple samples and may produce inaccurate crop N rate requirement estimates.

Nitrogen Rate Determination Based on Spectral Derived Index

Remotely sensed crop spectral properties have been used to assess multiple crop parameters such as photosynthetic capacity, productivity and potential yield (Penuelas et al., 1994; Aparicio et al., 2000; Thenkabail et al., 2000; Ma et al., 2001; Raun et al., 2001; Baez-Gonzales et al., 2002; Teal et al., 2006a). These crop biophysical traits have been utilized in various ways to determine optimum crop N requirements. Stone et al. (1996) correlated plant N spectral index and total N uptake to determine N requirement in winter wheat. Other studies correlated spectral measurements to plant biomass (Wallburg et al., 1982; Kleman and Fagerlund, 1987; Wanjura and Hatfield, 1987; Casanova et al., 1988; Felton et al., 2002; Bronson et al., 2003) and plant N content (Blackmer et al., 1997; Bronson et al., 2003), parameters that can be used to estimate crop N requirements.

Spectral measurements have also been utilized by many researchers to determine yield potential using simple regression equations (Moran et al., 1997; Raun et al., 2001; Teal et al., 2006a). Yield potential is simply a function of all conditions of the growing environment (Johnson, 1991) and an integral component of the fertilizer N management decision. Raun et al. (2001) reported that yield potential can be predicted in-season using optical sensors. They used Normalized Difference Vegetation Index (NDVI; Rouse et al., 1973), the most widely used spectral vegetation index, to determine in-season estimated yield (INSEY). The index-INSEY, a measure of biomass produced per day, is the NDVI reading (Feekes growth stages 4 to 6; Large, 1954) divided by the number of growing degree days $\left(GDD = \frac{T_{max} + T_{min}}{2} - 4.4°C\right)$. The equation of the line that best described the relationship between INSEY and actual grain yield was used to estimate yield potential (YP_0). Raun et al. (2002) developed a functional algorithm (nitrogen fertilization optimization algorithm or NFOA) that can precisely estimate midseason N requirements of winter wheat. The projected midseason N requirement is based on N demand of the predicted YP_0 while taking into account seasonally dependent crop responsiveness to applied N. Their work has shown that N use efficiency (NUE) of winter wheat was improved by more than 15% when this approach was employed compared with conventional N rate recommendations. Arnall et al. (2006) used the coefficient of variation (CV) from NDVI readings to evaluate plant-stand densities in winter wheat. Using a linear plateau model, they reported that a <100 plants m^{-2} population having a CV value of 20% was considered a poor stand. Raun et al. (2005) used this information to further refine the algorithm. The mathematical adjustment in the algorithm using CV is important in areas with pronounced spatial variability. In the algorithm, when the CVs of the sensed area become higher than the 20 % critical CV, the N rate recommendation decreases, and vice versa when the CV is low. The successful use of sensor-based N rate recommendations in winter wheat prompted the development of a functional algorithm for equally important crops like corn.

HYPOTHESIS AND OBJECTIVES

The hypothesis of this study was that estimating N rate requirements based on N demand for a given projected corn yield potential would result in improved grain yield, NUE, and net return. The objectives of this study were to determine the nitrogen fertilization optimization algorithm (NFOA) that could be used to estimate midseason N rates for optimum corn growth and to determine the optimum resolution to treat spatial variability in corn.

MATERIALS AND METHODS

Field trials were established on a Easpur loam soil (fine-loamy, mixed, superactive, thermic Fluventic Haplustolls) located at the Stillwater (EFAW) Research Station, on a Pulaski fine sandy loam soil (coarse-loamy, mixed, superactive, nonacid, thermic Udic Ustifluvents) at Lake Carl Blackwell Research (LCB) Station and on a Teller sandy loam soil (fine-loamy, mixed, active, thermic Udic Argiustolls) at the Perkins Research Station, Oklahoma. Before crop establishment, comprehensive soil samples at 0-15 cm were collected, air-dried and processed to pass 2 mm sieve for Mehlich III-extractable phosphorus (P), exchangeable potassium (K), NH_4-N and NO_3-N determination (Table 1). The experiments consisted of 13 treatments arranged in randomized complete block design or RCBD (Table 2). Treatments included: a check plot; a 134 kg N ha^{-1} fixed rate applied in split, preplant- and sidedress-only; a 67 kg N ha^{-1} fixed rate applied preplant- and sidedress-only; three NFOA-based midseason N rates (RICV-NFOA, RI-NFOA, flat-RICV-NFOA) with (67 kg N ha^{-1}) and without preplant N; and two resolutions (0.34 and 2.32 m^2) tested for RICV-NFOA only. The flat-RICV-NFOA-based midseason N rates were determined from the average of the variable rates determined by the RICV-NFOA.

Table 3 provides information on field activities, corn varieties and planting rates for each site for 3 cropping years. Plots with corresponding preplant N were treated either before or at planting. The NDVI readings and CVs were collected before sidedress application. The GreenSeeker™ hand held optical sensor (NTech Industries, Inc.) was used to measure NDVI at a distance of 0.6 to 1.0 m from the corn canopy. The GreenSeeker sensor calculates NDVI using the equation:

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}}$$

where:

ρ_{NIR} = fraction of emitted near-infrared (NIR) radiation (780±10 nm) returned from the sensed area

ρ_{RED} = fraction of emitted red radiation (671±10 nm) returned from the sensed area

The NDVI readings when divided by the number of days from planting to sensing will give INSEY which is an index of biomass produced on a daily basis and can be used to predict YP_0 using the algorithm for corn (Teal et al., 2006a). Yield potential when N is applied (YP_N) was determined by multiplying YP_0 by the response index (RI_{NDVI}: NDVI in the 134 kg N ha^{-1} preplant treated plot divided by NDVI in check plot collected at V8). The N rate required to achieve the YP_N for each plot was computed using the equation:

$$R_n = \frac{YP_0 N_g}{\varepsilon_n}(RI - 1)\left(\frac{CV_{Cap} - CV_{Plot}}{CV_{Cap} - CV_{Critical}}\right)$$

where:

R_n = N application rate, kg ha^{-1}

N_g = N content in grain, 0.0125 kg N kg^{-1}

ε_n = Expected NUE

RI = Adjusted RI, $\left(\frac{NDVI_{N-Rich}}{NDVI_{Farmer}} \times 1.64\right) - 0.528$

CV_{Cap} = Maximum coefficient of variation

$CV_{Critical}$ = Critical coefficient of variation value

CV_{Plot} = Coefficient of variation from the plot's NDVI readings

Table 4 presents the YP_0 equations, critical and maximum CVs, and the number of days from planting (DFP) to sensing for each site year. In 2005, the critical CV was determined based on plant population using the linear equation: y = (-0.0003 x plant population) + 36.315 (www.nue.okstate.edu). Flat and varied amounts of N were applied as urea ammonium nitrate (UAN, 28-0-0) at the base of the plants of designated subplots using syringes (± 0.1 mL).

Two middle rows of the plots were harvested with a Massey Ferguson 8XP combine. Grain yield and percent moisture content were collected using a Harvest Master yield monitoring computer. Moisture content of the final grain yield was adjusted to 15.5%. Grain subsamples were collected, oven-dried at 70°C until no further loss in weight was observed and processed to pass 106 um (140 mesh screen) for total N analysis using a Carlo Erba Na 1500 dry combustion analyzer (Schepers et al., 1989). Total N uptake was determined by multiplying percent N in grain with grain yield. NUE was determined by dividing the difference in grain N uptake of fertilized and check plots by the N rate applied. Net return to N fertilizer was computed by subtracting the cost of total N applied from gross income (price of grain in kg multiplied by grain yield). Table 5 provides the prices of N fertilizer and wheat grain from 2004-2006 used in net return determination. Statistical analysis was performed using SAS for Windows (SAS, 2002). Analysis of variance (ANOVA) was conducted to determine if there were significant differences among treatment means of the variables measured: yield, grain N uptake, NUE and net return. SAS Mixed Model Procedure was used to partition sources of variation.

RESULTS

Components of the Nitrogen Fertilization Optimization Algorithm

Estimates of Yield Potential

Teal et al. (2006a) reported that NDVI and its derived indices can be used to estimate corn YP_0 when sensing is accomplished between V7-V9 leaf growth stages. They reported that NDVI measured at V8 was highly correlated with actual grain yield (R^2 = 0.77). Table 6 reports the average NDVI readings of the check plot. The actual grain yields increased with increasing NDVI readings. The highest NDVI reading (0.83) collected at LCB in 2005 obtained an actual yield of 9947 kg ha^{-1}, the highest check plot's yield recorded in the trial. Teal et al. (2006a) also found that a strong relationship existed between NDVI normalized by the number of days from planting to sensing (DFP INSEY) and actual grain yield (r^2 = 0.74). In this trial, the equation derived from the relationship between NDVI-derived-index DFP INSEY and actual yield was used to estimate corn grain yield potential. In general, estimated yield potential was close to measured grain yield (Table 6). At Perkins, the method for estimating yield potential (YP_0 = 5256 kg ha^{-1}) was close to actual grain yield (5343 kg ha^{-1}). However, as has been reported, yield potential can be overestimated using this approach (Raun et al., 2005). Obtaining accurate estimates of yield potential relies on fitting a model not adversely affected by changes in growth conditions otherwise, YP_0 can be over- or underestimated. This was exemplified at LCB in 2005 and at Perkins in 2006. The discrepancy obtained at Perkins was attributed to the moisture stress that occurred between sensing and harvest that adversely affected YP_0. As a result, the estimated YP_0 at 4617 kg ha^{-1} was higher than the actual yield (1935 kg ha^{-1}). At LCB, canopy closure at V8 leaf growth stage resulted in very high NDVI readings averaging 0.82 (Table 7). At this NDVI value, the sensor was exclusively measuring plant material. Since the DFP INSEY was used, the NDVI readings were normalized by DFP which was reported to be the lowest number (49 days) obtained in all site years (Table 6). The projected biomass produced per day was large because of the high NDVI reading and relatively low DFP. The equation projected what would be the final yield potential with the biomass produced per day. Thus, YP_0 was large for this specific site year, and the amount of N in the check plot could have become limiting as plant growth continued. As a result, crop growth rate slowed down within the period from sensing towards harvest that caused a reduction in the final grain yield. This resulted in a large discrepancy of YP_0 (21,806 kg ha^{-1}) and actual grain yield (9947 kg ha^{-1}) of the check plot. The LCB Research Station has been under irrigation since the spring of 2005. The non-limiting moisture at this site resulted in a lower number of days to reach V8 leaf growth stage (faster growth rate) compared with the rainfed system at Efaw and Perkins (Table 6). Perkins has a sandy loam soil known to have poor water holding capacity. As a result of a less favorable growing conditions at this site, average grain yields were lower than at Efaw and LCB (Table 6).

Response Index

Response index at harvest ($RI_{HARVEST}$) was determined by computing the ratio of grain yield of the highest N fertilized plot and grain yield of the check plot (Table 6). Corn N response varied by year and location. The RI_{NDVI} was adjusted by using a previously established relationship between vegetative response (RI_{NDVI}) and grain yield response ($RI_{HARVEST}$) to N fertilization. The adjusted RI_{NDVI} values [(RI_{NDVI} x 1.64) – 0.528] generally provided good estimates of actual crop response to fertilizer N (Table 6). In some site years however, the response of corn to N fertilization was underestimated as shown in 2006 at Efaw, where a difference of 0.74 existed between predicted (RI_{NDVI} = 1.34) and observed response ($RI_{HARVEST}$ = 2.08) to N. Mullen et al. (2003) explained that after sensing, enhancing and limiting factors affecting crop yield potential may occur that lead to underestimation or overestimation of $RI_{HARVEST}$ by RI_{NDVI}. Further, they explained that favorable conditions that occurred (such as timely rainfall) after sensing can increase crop N response resulting in a higher $RI_{HARVEST}$ value than RI_{NDVI}. At Perkins in 2006, this was the only site year where $RI_{HARVEST}$ (1.28) was underestimated by RI_{NDVI} (1.52). This exemplifies growth conditions that adversely affect crop N response between sensing to harvest. In 2005, a state-of-the-art irrigation system was installed at LCB. With this system, moisture stress can be avoided and thus, crop growth conditions were near ideal. Since 2005, RI_{NDVI} provided accurate estimates of crop response to N. The RI_{NDVI} and $RI_{HARVEST}$ for 2005 at LCB were 1.42 and 1.44, respectively. Similarly, close RI values are reported between estimated (RI_{NDVI} = 1.94) and observed ($RI_{HARVEST}$ = 1.92) in 2006 at LCB (Table 6). The absence of drastic changes in growth conditions resulted in little or no change in crop response to N from sensing to harvest at this particular site.

Coefficient of Variation

Initially, critical CV used in the algorithm was 20% (Arnall et al., 2006) and a maximum CV value to cap mathematical adjustment by the CV component (Table 4). Recent studies conducted showed that critical and cap CV should be adjusted for the corn algorithm. Teal et al. (2006b) obtained a maximum 55 % CV from the NDVI readings when the plant population was about 20,000 plant ha^{-1}. The highest CV from NDVI readings obtained by Martin et al. (2006) was 65% and thus, the cap CV used in the algorithms was adjusted from 100% to 65% in 2006. Further, Martin et al. (2006) reported that a strong correlation existed between corn plant density and CVs from NDVI readings measured between V7-V9 leaf growth stages. This implied that critical CV may change depending on the plant population and thus, an equation was established that allowed the adjustment of critical CV based on plant population. Table 8 presents the critical CV used in the RICV-NFOA treatments. The minimum, maximum and average CVs collected from treatments 7, 8 and 11 are also reported by site and year. With the given trend of critical CVs estimated by plant population, there were site years utilizing the 20%-critical CV that should have used only 13% (Efaw and LCB in 2004) (Table 8). A higher critical CV in these site years resulted in a higher N rate recommendations by RICV-NFOA.

Nitrogen Fertilizer Recommendations

Fixed and Midseason NFOA-Based N Rates

The total N applied for each treatment is summarized by site and year in Table 9. The highest fixed rate applied was 134 kg N ha^{-1} while the NFOA-based N rate applied was 199 kg N ha^{-1} at Efaw in 2005. Table 7 presents the sidedress N rate applications for each treatment by site and year. Amounts of N fertilizer applied in treatments 7 to 13 had wide variation across site years. The lowest sidedress N rate recorded was only 1 kg N ha^{-1} at LCB and the highest (132 kg N ha^{-1}) was at Efaw, both in 2005. These varying levels of N demonstrated the ability of the algorithms to adjust N based on YP_0, crop responsiveness and plant-stand/density, all derived from NDVI readings of the current crop.

Midseason NFOA-Based N Rates With and Without Preplant

To determine midseason NFOA-based N rate requirements, YP_N needs to be determined first. In 2004 and 2005 for all sites, the RI_{NDVI} was determined by dividing the NDVI readings of treatment 6 (134 kg N ha^{-1} fixed rate applied preplant) by the check plot. This RI_{NDVI} was used regardless of whether the NFOA-based N rates received preplant N. Generally, the resulting recommendations for NFOA-treatments with 67 kg N ha^{-1} preplant tended to be higher than NFOA-treatments without preplant (Table 7). The 67 kg N ha^{-1} fixed rate applied preplant provided modest amounts of N for early corn establishment. This resulted in healthier corn plants and higher NDVI readings than corn plants without preplant N. To account for the amount of N that was applied preplant, in 2006, the RI_{NDVI} for NFOA-treatments with preplant N was determined by dividing the NDVI readings of treatment 6 by treatment 5 (67 kg N ha^{-1} fixed rate applied preplant). This made sense since for corn with preplant N, higher NDVI readings obtained at V8 leaf growth stage would not only mean higher YP_0 but also more vigor enhanced by extra N from preplant application available from the early stages of growth until V8 (sensing time). With this alteration, midseason N rate requirements prescribed by NFOA with preplant N were lower than NFOA without preplant which should be expected since a portion of the total N requirements was already applied early in the season.

RICV- and RI-NFOA-Based N Rates

The integration of CVs in the NFOA was proposed by Raun et al. (2005). Further refinement of the algorithm was required for fields of wheat where variation in crop stand was so pronounced that it masked the average NDVI readings. When plot CVs exceeded the critical CV set in the algorithm, the final midseason N rate recommendations were less. It was presented that critical CV in earlier years was set at 20%, based from the results reported by Arnall et al. (2006). Table 7 provides actual critical CVs when determined based on plant population. The actual critical CVs in 2004 and 2005 were overestimated. At Efaw in 2004 and 2005, midseason RICV-NFOA recommended N rates that ranged from 100 to 127 kg N ha^{-1} (Table 10). On the other hand, the midseason N rate recommendations using RI-NFOA ranged only from 31 to 66 kg N ha^{-1}. The RICV-NFOA resulted in higher recommendations for these site years because CVs from NDVI readings were lower than the critical CV set at 20%. Predicted YP_N starts to decline only when CV from NDVI readings exceeds the critical CV. Using an average of 8% CV (Table 8) collected at Efaw in 2004, the adjustment made by the CV component $\left(\frac{CV_{Cap} - CV_{Plot}}{CV_{Cap} - CV_{Critical}}\right)$ for YP_N using a critical CV of 20% was 1.26. However, when using the actual critical CV of 13% that was derived from plant population (Table 8), the adjustment made by the CV component would have only been 1.10 to obtain the YP_N.

Table 10 shows the midseason N rate recommendations made by NFOA by site and year. The algorithm that utilized CVs had a wider range of midseason N rate recommendations. The highest range of midseason N rates was observed at Perkins in 2005. We recorded a minimum of 0 and a maximum of 201 kg N ha^{-1} taking note that this site year also obtained the highest average CV of 27% (Table 8). The RI-NFOA generally resulted in the lowest amounts of midseason N by site year, and ranged from 8 to 67 kg N ha^{-1}. In 2006, it is important to note that while there were large differences in minimum and maximum midseason N rates of the RI- and RICV-NFOA, the average midseason N rates of the two algorithms did not deviate as much. The CV component helped to recognize that N fertilization would be unnecessary in subplots with poor stands and N fertilization at rates higher than what RI-NFOA recommended in subplots with homogenous stand.

Excluding Efaw in 2006, RICV-NFOA projection at 2.32 m^2 resolution had smaller disparity in the minimum and maximum midseason N rates applied (Table 10). Further, the average midseason N rates at this resolution were also lower than what RICV-NFOA projected at 0.34 m^2 resolution. A similar trend was observed when minimum, maximum and average CVs collected from these application resolutions were compared (Table 8).

Responses of Measured Variables to Fixed and NFOA-Based N Rates

Grain Yield

Grain yields and the response to N fertilizer applied at fixed and variable rates are presented in Table 6. The standard error of the difference between two equally replicated means (SED) is also reported. Grain yield means were significantly different (Pr>0.05) among treatments for all site years excluding Perkins in 2006. Soil moisture in this site year became limiting compounded by poor water holding capacity of the soil that masked the effect of N application at different rates on grain yield. On the other hand, on average by site, Efaw's and LCB's treatment 13 (RI-NFOA with 67 kg N ha^{-1} preplant) obtained the highest grain yields at 12763 and 10760 kg ha^{-1}, respectively. At Efaw, this treatment received only a total of 108 kg N ha^{-1} compared with the fixed rate at 134 kg N ha^{-1} split applied (Table 7). At LCB, total N applied to this treatment equalled treatment 4.

At Perkins, treatment 4 (134 kg N ha^{-1} split applied) produced the highest grain yield at 5758 kg ha^{-1}. Whether fixed or NFOA-based, plots consistently produced higher grain yields when modest amounts of preplant N were applied (67 kg ha^{-1}). One-time 134 kg N ha^{-1} application (treatment 3) benefited corn grain planted at Efaw and LCB when compared with plots that did not receive preplant N. However, this was not the case at Perkins. The drier conditions at Perkins because of this soil's poor moisture holding capacity may have resulted in N lost via volatilization early on.

Within the NFOA-treatments with preplant N, the maximum grain yield difference attained was 1197 kg ha^{-1} at LCB. Grain yields ranged from 11610 to 12763 kg ha^{-1} at Efaw, 9568 to 10760 kg ha^{-1} at LCB, and 5133 to 5332 kg ha^{-1} at Perkins. Treating the plots at 0.34 m^2 resolution resulted in a higher grain yield at Efaw. On average, using RICV-NFOA at 0.34 m^2 obtained 12308 kg ha^{-1} while at 2.32 m^2, grain yield was only 11610 kg ha^{-1}. There was no pronounced benefit when plots were treated at 0.34 m^2 resolution at LCB and Perkins. Flat-RICV-midseason N rates were determined by using average N estimates by RICV-NFOA. Unlike RICV-NFOA, flat-RICV-NFOA distributed N fertilizer in the entire corn row. Grain yields between RICV- and flat-RICV-NFOA had minimal differences. In some site years, flat-RICV's grain yield tended to be higher and lower in others.

Grain N Uptake

The total grain N uptake in response to N fertilizer application is presented in Table 11 by treatment, site and year. The SED values by site and year are also reported. Excluding Efaw in 2004, mean grain N uptake was significantly different ($Pr>0.05$) among treatments across site years. Applying 134 kg N ha^{-1} either preplant or sidedress (treatment 3 and 6) at Perkins resulted in lower grain N uptake compared when N was split (treatment 4). Grain N uptake was only 76 kg N ha^{-1} for both treatment 3 and 6 compared with 93 kg N ha^{-1} for treatment 4. Perkins is considered as a low yielding environment for corn thus the absence of N (treatment 3) at early growth stages affected crop yield potential, even if large amounts of N were applied at later stages, the crop failed to catch up. Similarly, excess N as a result of large applications at early growth stages under dry and hot conditions at Perkins enhanced the process of N loss via volatilization. At LCB, marginal differences among N uptake of these treatments were obtained. Grain N uptake values were 168, 165 and 160 kg N ha^{-1} for treatment 3, 4 and 6, respectively. At Efaw, both N uptake of treatment 4 (170 kg N ha^{-1}) and 6 (176 kg N ha^{-1}) were comparable but not for treatment 3 (152 kg N ha^{-1}).

On average by site, the highest N uptake obtained was 200 kg N ha^{-1} at Efaw (treatment 13). A 30 kg N ha^{-1} difference was recorded when treatment 13 was compared with treatment 4. At Efaw, the NFOA-treatments with 67 kg N ha^{-1} preplant had higher N uptake compared with the treatments that received 134 kg N ha^{-1} (split, preplant- or sidedress-only). However, this was not observed at LCB and Perkins. While treatment 4 recorded the highest grain N uptake for these two sites, the difference it made compared with treatment 13 was minimal. At Perkins, treatment 4 had 93 kg N ha^{-1} while treatment 13 had 86 kg N ha^{-1}. Treatment 4 at LCB obtained 165 kg N ha^{-1} while a very close value of 162 kg N ha^{-1} was obtained by treatment 13.

The use of RI-NFOA (treatment 13) resulted in higher grain N uptake when compared with RICV-NFOA (treatment 8) at Efaw and LCB but not at Perkins. Treatment 8 had grain N uptake values of 181, 138 and 87 kg N ha^{-1} while treatment 13 had 200, 162 and 162 kg N ha^{-1} at Efaw, LCB and Perkins, respectively. Treating plots at different resolutions using RICV-NFOA did not result in large N uptake differences. Similarly, utilizing the average of RICV-NFOA for uniform N rate application resulted in minimal differences in grain N uptake.

Nitrogen Use Efficiency

Nitrogen use efficiency of each treatment is presented by site and year in Table 12. On average by site, split applications of N resulted in minimal differences in NUE when compared with preplant or sidedress only at LCB. At 134 kg N ha^{-1} fixed rate, NUE values were 68, 69 and 63 for sidedress, split and preplant application, respectively. At Perkins, when N was split applied, a higher NUE difference (13%) was obtained when compared with preplant- and sidedress-only. Preplant N application (58%) had a minimal advantage in NUE when compared with split at Efaw (54%). Efaw is a high yielding site (Table 11) compared with Perkins thus, preplant N was required for early growth establishment because of a relatively high yield potential at this site. Late application of 134 kg N ha^{-1} at V8 did not help the corn plant to catch up which resulted in lower grain yield (10251 kg ha^{-1}) and lower N uptake (152 kg N ha^{-1}) when compared with split application (11094 kg ha^{-1} grain yield and 170 kg ha^{-1} N uptake).

On average, the NFOA treatments with preplant N obtained higher NUE values compared with 134 kg N ha^{-1} split applied. The highest was obtained by treatment 13 (83%) at Efaw, treatment 13 (69%) at LCB, and treatment 11 (43%) at Perkins. Without preplant N, RI-NFOA obtained the highest NUE of 83% at LCB while the RICV-NFOA at Perkins had the highest NUE at 59%. Treating plots at 0.34 m^2 application resolution resulted in improved NUE only in low yielding environments and when spatial variability was pronounced (Perkins). The flat-RICV's NUE values were consistently lower than the RICV-NFOA's, however minimal differences were recorded at 2, 2 and 4% at Efaw, LCB and Perkins, respectively.

At Perkins, RICV-NFOA with preplant obtained the highest NUE value because of lowest total N input. At LCB, the high NUE value of the RI-NFOA was attributed to a large reduction in total N applied but as well the grain yield it produced was within the upper end among the treatments. The use of RI-NFOA (with preplant N) resulted in the highest NUE among treatments. The benefit of using RI-NFOA in improving NUE was attributed to increased grain yield, N uptake and reduced fertilizer N input.

Net Return to Nitrogen Fertilizer

Net return, computed by subtracting the cost of fertilizer from gross income (grain yield x grain price kg^{-1}), is presented in Table 13 by treatment, site and year. Differences in net return were significant ($Pr>0.05$) among treatment means excluding LCB in 2005 and Perkins in 2006. At Perkins, the response to N was masked by the more limiting effect of moisture stress, as a result, no significant differences ($Pr>0.05$) in grain yields among treatments were obtained as reported in Table 6. This caused treatments to obtain comparable gross incomes. Further, the savings on the cost of fertilizer in some of the treatments did not compensate for the slight reduction in grain yield in response to reduced N applied resulting in no significant differences in net returns.

On average, both fixed and NFOA-based N rates with preplant obtained consistently higher net returns than treatments without preplant N. The highest net return obtained was $1344 ha^{-1} at EFAW, achieved when midseason N rates were based on RI-NFOA. The RICV-NFOA net return was second highest with $ 1254 ha^{-1}. At LCB, a fixed rate of 134 kg N ha^{-1} split applied obtained the highest net return at $ 1112 ha^{-1}. The RI-NFOA's net return of $ 1089 ha^{-1} was within the upper end but not the RICV-NFOA which achieved only $ 903 without preplant and $ 968 with preplant N. At Perkins, 134 kg N ha^{-1} applied in split obtained the highest net return of $ 528 ha^{-1} followed by the 67 kg N ha^{-1} rate preplant applied ($ 517 ha^{-1}). Both RI- and RICV-NFOA with preplant achieved net returns that were within the upper end group amounting to $ 477 and $ 480 ha^{-1}, respectively.

With preplant N, treating plots at 0.34 m^2 resulted in higher net return at Efaw, ($ 1254 versus $ 1171) than when using 2.32 m^2- resolution. However at LCB and at Perkins, net return obtained was slightly higher at 2.32 m^2- than at 0.34 m^2- resolution. The flat-RICV's net return did not record consistent trends across site years. The highest deviation from the RICV-NFOA's net income was $ 53 ha^{-1}.

Efaw was the only site that obtained the highest net return using the algorithm (RI-NFOA) to determine midseason N rates. This was attributed to increased grain yield and reduced N fertilizer input. At LCB, the net returns achieved by RI-NFOA were still within the upper end group. This can be attributed to relatively higher midseason N rates projected by the algorithm that almost equalled the 134 kg N ha^{-1} fixed rate. At Perkins, both RI- and RICV-NFOA treatments had net returns within the upper end group.

DISCUSSION

The concept of using the demand for N of the projected YP_0 to estimate crop N requirements is a better option than applying fixed N rates every cropping season. Based on our results, unless significant changes in growth conditions occurred after sensing, the YP_0 equation obtained reasonable estimates of actual grain yield. This implies that INSEY, an estimate of biomass produced per day, works but needs to be more robust i.e., should be accompanied by more risk averse prediction models. Crop response to N application as estimated by the RI was adjusted using the equation of the linear relationship between RI_{NDVI} and $RI_{HARVEST}$. The adjustment made on RI resulted in good estimates of corn response to N fertilization for most site years especially at LCB, an irrigated site, where growth conditions were near ideal. The RI_{NDVI} overestimated crop response to N when adverse growth condition occurred after sensing that masked the effect of N to crop growth as exemplified at Perkins.

Total N applied to treatments that utilized the NFOA approach were highly varied ranging from 31 to 168 kg N ha^{-1}. It is important to take note that extremely low N rates projected by the NFOA did not result in a drastic reduction of grain yields. While the NFOA in some site years had lower yield compared with the flat rates, the large reduction in N fertilizer applied resulted in a higher NUE. Further, the large reduction in cost of N fertilizer outweighed the benefit of increased grain yield of plots applied with the 134 kg N ha^{-1} fixed rate. In addition to a considerable reduction in the cost of N fertilizer used, grain yield of the NFOA-based approach with preplant N (67 kg N ha^{-1}) in some site years exceeded the grain yield of the 134 kg ha^{-1} fixed rate split applied. This demonstrates that the NFOA approach is very promising in terms of improving producers' income.

The inclusion of a CV component made the RICV-NFOA different from the RI-NFOA. The CV component allows the algorithm to take into account field spatial variability and helps determine if there is a need to adjust N rates depending on crop stand/density, such that a good homogenous stand would receive more N fertilizer than a poor plant stand. While this trend was demonstrated based on the total N applied in the RICV- and RI-NFOA plots, the expected benefits in grain yield, NUE and net return was not exhibited by RICV-NFOA at high yielding site years. Likewise, while the RI-NFOA approach excelled at high yielding site years, it was limited by adverse growth conditions whereas RICV-NFOA performed better in terms of increasing NUE. These observations imply that a) the use YP_0 and adjusted RI_{NDVI} as components of algorithm can improve NUE and net returns attributed either to increased grain yield or large savings due to lower N rates applied provided that the crop is under near ideal growing conditions, b) CV components will play an important role in improving the algorithm especially when pronounced spatial variability brought about by unfavorable growth conditions, and c) CV components require improved mathematical adjustment to work in well established, homogenous crop stand.

There was no pronounced trend between the two resolutions (0.34 and 2.32 m^2) tested when comparing grain yields, NUE and net returns. Moreover, the flat-RICV-NFOA showed comparable grain yields, NUE and net returns with RICV-NFOA's. These results suggest that the RICV-NFOA recommendation from a good representative area of a farmer's field thus far can be used to make uniform recommendation for an entire field. While the algorithm recommend uniform rates, this approach still encumbers the N demand based on predicted YP_0, field spatial variability, and the seasonally dependent crop responsiveness to applied N. This is very important in fields where variable rate application is not feasible.

CONCLUSION

While the algorithms used to estimate midseason N rates have required several adjustments on RI_{NDVI} and CV components, they have consistently led to increases in the variables measured. The refinement made along the course of the trial by adjusting CVs and RI_{NDVI} resulted in relatively higher midseason N rate estimates and yet maintained the ability of the NFOA to obtain improved grain yield, NUE, and net return. This study also demonstrated the benefit of applying N fertilizer on a need-basis over uniform applications of N based on historical crop information.

On average, with modest amounts of preplant N, midseason RI-NFOA-based N recommendation improved NUE to 64% compared with 56% of the 134 kg N ha^{-1} fixed rate split applied. The use of the RI-NFOA also improved grain yields in four of six high yielding site years and net returns in three of six high yielding site years. At Perkins (low yielding site), the 134 kg N ha^{-1} fixed rate split applied obtained the highest grain yield and net return while the RI-NFOA's were comparable. The RICV-NFOA without preplant N showed an advantage over RI-NFOA in improving NUE when field variation became pronounced as a result of unfavorable growth conditions. Without preplant N in low yielding site years, the RICV-NFOA had a higher NUE (59% versus 43%) and net return ($ 475 versus $ 401 ha^{-1}) compared with the RI-NFOA's. With preplant N on the other hand, NUE and net returns of RICV- and RI-NFOA were comparable. The increase in NUE can be attributed to reductions in N fertilizer input recommended by the RICV-NFOA. There was no improvement in NUE and net returns when spatial variability was treated at 0.34 m^2 using the RICV-NFOA. Using an average of midseason N rates prescribed by RICV-NFOA for uniform application of N fertilizer (flat-RICV-NFOA) may result in minimal differences in grain yield, NUE and net return. In general, the use of midseason sensor-based predictions of YP_0 and RI_{NDVI} provided accurate rate recommendations when compared with flat rates.

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Table 1. Soil chemical properties determined from initial soil samples (0-15 cm) at three locations, Oklahoma.

Site	pH	g kg^{-1}		mg kg^{-1}			
		Total N	Total C	NH_4-N	NO_3-N	P	K
EFAW	5.9	0.65	10.24	13.9	3.7	20	90
LCB	5.6	0.76	9.87	28.4	4.4	45	144
Perkins	6.2	0.44	6.4	9.2	8.1	14	118

pH – 1:1 soil:water; K and P – Mehlich III; NH_4-N and NO_3-N – 2 M KCl, Total N and Organic C – dry combustion.

Table 2. Treatment structure and description used for the trials conducted at Efaw, Lake Carl Blackwell and Perkins, 2004-2006.

Treatment	Preplant N kg ha^{-1}	MidSeason N kg ha^{-1}	Resolution m^2
1	0	0	-
2	0	67	-
3	0	134	-
4	67	67	-
5	67	0	-
6	134	0	-
7	0	RICV-NFOA	0.34
8	67	RICV-NFOA	0.34
9	0	Flat-RICV-NFOA	-
10	67	Flat-RICV-NFOA	-
11	67	RICV-NFOA	2.32
12	0	RI-NFOA	0.34
13	67	RI-NFOA	0.34

NFOA = Nitrogen Fertilization Optimization Algorithm
RICV-NFOA = algorithm for adjusting mid-season N rate recommendation for the predicted yield potential using response index and coefficient of variation as the components
Flat-RICV-NFOA = utilized the average of N rates determined by RICV-NFOA
RI-NFOA = algorithm for adjusting midseason N rate recommendation for the predicted yield potential using response index

Table 3. Field activities for all sites and years, 2004-2006.

Site	Year	Variety	Planting Rate plants ha^{-1}	Date±			
				Planting	Sensing¶	Sidedress Application	Harvest
EFAW	2004	113 BT	66,000	04-07-04	06-01-04	06-02-04	09-03-04
	2005	38B51	59,000	03-30-05	05-25-05	05-25-05	08-27-05
	2006	38B51	54,000	03-30-06	05-24-06	05-24-06	09-01-06
LCB§	2004	108 BT	66,000	04-03-04	06-11-04	06-12-04	08-27-04
	2005	38B51	74,000	04-12-05	05-31-05	05-31-05	09-07-05
	2006	38B51	79,000	03-31-06	05-22-06	05-23-06	08-18-06
Perkins	2004	108 BT	59,000	04-02-04	06-03-04	06-07-04	09-01-04
	2005	8454Y61	49,000	03-28-06	06-06-05	06-06-05	08-31-05
	2006	OKC5020	49,000	03-30-06	05-30-06	05-30-06	08-14-06

± Date in month-day-year
§ Lake Carl Blackwell
¶ Sensing dates done between V8-V9 leaf growth stages.

Table 4. Yield potential equations, coefficients of variation and days from planting to sensing that were used to compute midseason nitrogen rate requirements, 2004-2006.

Year	YP_0 Equations	Coefficient of Variation, %		DFP		
		Critical	Cap	Efaw	LCB	Perkins
		-------------CV, %-------------		---------No. of Days-------		
2004	YP_0 = 1333*exp(INSEY*122.46)	20	100	50	65	61
2005	YP_0 = 1565*exp(INSEY*154.7)	20	100	56	49	68
2006	YP_0 = 1202*exp(INSEY*169.6)	§	65	56	53	62

CV = coefficient of variation
YP_0 = yield potential
INSEY = in-season estimated yield computed by dividing NDVI readings at V8 leaf growth stage divided by the number of days from planting to sensing
§ Determination of critical CV was based from plant population.
DFP = number of days from planting to sensing
Cap = set maximum CV value

Table 5. Prices of nitrogen fertilizer and corn grain used for net return computation, 2004-2006.

Year	Grain Price† $ kg^{-1}	Price N Fertilizer‡ $ kg N^{-1}
2004	0.104	0.59
2005	0.098	0.71
2006	0.133	0.75

† Source: USDA, NASS.
‡ Estimated U.S. farm level fertilizer prices, Source: US Department of Energy.

Table 6. Corn grain yield response to nitrogen fertilizer at Efaw, Lake Carl Blackwell and Perkins, 2004-2006.

N Applied		Efaw				Lake Carl Blackwell				Perkins			
Preplant	Midseason[¥]	2004	2005	2006	**Avg.**	2004	2005	2006	**Avg.**	2004	2005	2006	**Avg.**
---------kg N ha^{-1}---------		---------------Grain yield, kg ha^{-1}---------------											
0	0	9518	6206	5458	**7061**	4167	9947	4724	**6279**	5343	1860	1935	**3046**
0	67	13122	9928	9395	**10815**	7559	12590	7853	**9334**	6841	4120	2282	**4414**
0	134	11798	10146	8808	**10251**	7154	13896	10664	**10571**	7149	3803	2857	**4603**
67	67	13405	10288	9590	**11094**	8845	14297	9712	**10951**	8749	5262	3264	**5758**
67	0	12391	9184	8195	**9923**	7876	12886	5808	**8857**	7612	4935	3118	**5222**
134	0	13286	11245	11337	**11956**	7852	14273	9116	**10414**	7998	4269	2485	**4918**
0	RICV-NFOA	11186	8555	6912	**8884**	6172	11992	7592	**8585**	7063	4111	3180	**4785**
67	RICV-NFOA	13890	11971	11062	**12308**	7802	13036	7866	**9568**	7905	5083	3007	**5332**
0	Flat-RICV-NFOA	13476	9367	9118	**10654**	6618	11142	7616	**8459**	7036	3330	2388	**4251**
67	Flat-RICV-NFOA	13341	11482	10259	**11694**	8662	12996	8356	**10004**	8089	4960	2351	**5133**
67	RICV-NFOA	13336	11375	10118	**11610**	8580	13524	6821	**9641**	8469	4856	2464	**5263**
0	RI-NFOA	12862	10079	9241	**10727**	6818	13861	9459	**10046**	6698	3418	2236	**4117**
67	RI-NFOA	13997	12373	11920	**12763**	8380	14550	9349	**10760**	8423	4858	2649	**5310**
Pr>F		0.0068	0.0006	0.4503	-	0.0001	0.0045	0.0001	-	0.0001	0.0001	0.5985	-
Adj. RI_{NDVI}[†]		1.10	1.26	1.34	-	1.40	1.42	1.94	-	1.26	1.62	1.52	-
$RI_{HARVEST}$[¶]		1.39	1.81	2.08	-	1.88	1.44	1.92	-	1.50	2.30	1.28	-
$NDVI_{CHECK}$[§]		0.77	0.64	0.67	-	0.70	0.83	0.47	-	0.68	0.41	0.49	-
YP_0[‡]		8869	9000	9220	-	5021	21806	5335	-	5256	3979	4617	-
SED		705	829	131	-	574	763	636	-	351	333	450	-

† Adjusted in-season response index, determined by dividing average normalized difference vegetation index (NDVI) between V8-V9 leaf growth stage of treatment 6 (134 kg ha^{-1} preplant) by the Check. Adjustment was made using the equation (RI_{NDVI}x1.64) - 0.528.
¶ Response index at harvest, determined by dividing the grain yield of the highest preplant N fertilized plots by Check plot.
§ Average NDVI of the check plot.
‡ Predicted yield potential of the check plot in kg ha^{-1}.
¥ Full description is presented in Table 2.
SED = standard error of the difference between two equally replicated means

Table 7. Sidedress nitrogen fertilizer applied at fixed and midseason NFOA-based rates at Efaw, Lake Carl Blackwell and Perkins, 2004-2006.

N Applied		Efaw				Lake Carl Blackwell				Perkins			
Preplant	Midseason¥	2004	2005	2006	**Avg.**	2004	2005	2006	**Avg.**	2004	2005	2006	**Avg.**
---------kg N ha^{-1}---------		----------------------------------Sidedress N Applied, kg ha^{-1}---											
0	0	0	0	0	**0**	0	0	0	**0**	0	0	0	**0**
0	67	67	67	67	**67**	67	67	67	**67**	67	67	67	**67**
0	134	134	134	134	**134**	134	134	134	**134**	134	134	134	**134**
67	67	67	67	67	**67**	67	67	67	**67**	67	67	67	**67**
67	0	0	0	0	**0**	0	0	0	**0**	0	0	0	**0**
134	0	0	0	0	**0**	0	0	0	**0**	0	0	0	**0**
0	RICV-NFOA	108	100	58	**89**	80	38	58	**59**	80	43	77	**67**
67	RICV-NFOA	101	127	52	**93**	85	23	36	**48**	101	80	47	**76**
0	Flat-RICV-NFOA	108	100	58	**89**	80	38	58	**59**	80	43	77	**67**
67	Flat-RICV-NFOA	101	127	52	**93**	85	23	36	**48**	101	80	47	**76**
67	RICV-NFOA	99	132	58	**96**	87	1	19	**36**	109	35	31	**58**
0	RI-NFOA	31	66	48	**48**	48	98	87	**78**	66	64	56	**62**
67	RI-NFOA	32	66	24	**41**	50	107	43	**67**	83	85	23	**64**
Avg. NDVI		0.78	0.71	0.63	-	0.65	0.82	0.57	-	0.71	0.49	0.54	-
Avg. CV		8	14	14	-	12	10	17	-	15	26	16	-
Min CV		1	2	1	-	0	1	2	-	2	4	1	-
Max CV		31	54	52	-	98	44	57	-	66	55	54	-
CV Range		30	52	51	-	98	43	55	-	64	51	53	-

NDVI = normalized difference vegetation index
CV = coefficient of variation
NDVI and CV data were collected from midseason NFOA-based N rate treatments.
¥ Full description is presented in Table 2.

Table 8. Average, minimum and maximum coefficient of variation for three treatments employing the RICV-nitrogen fertilization optimization algorithm at the three locations, 2004-2006.

Year	Site	Critical CV, %		TRT 7 (0 - NFOA - 0.34)§			TRT 8 (67 - NFOA - 0.34)§			TRT 11 (67 - NFOA - 2.32)§		
		Used	Actual¶	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
		-----Coefficient of Variation, %-----										
2004	Efaw	20	13	1	20	7	2	31	8	5	17	8
	LCB	20	13	1	50	12	2	36	11	5	16	11
	Perkins	20	16	3	53	18	2	66	14	6	23	12
2005	Efaw	20	16	2	54	17	2	44	11	5	31	12
	LCB	20	10	1	44	13	1	33	7	2	11	4
	Perkins	19	19	8	54	27	4	55	23	18	31	48
2006	Efaw	18	18	4	44	15	1	52	14	4	30	12
	LCB	9	9	4	45	19	4	45	19	8	24	17
	Perkins	19	19	1	54	16	1	54	16	9	24	18

§ preplant – midseason N rates prescribed by NFOA – resolution.
¶ Determined from the equation: critical CV = (-0.0003*plant population) + 36.315.

Table 9. Total nitrogen fertilizer applied at fixed and midseason NFOA-based rates at Efaw, Lake Carl Blackwell and Perkins, 2004-2006.

N Applied		Efaw				Lake Carl Blackwell				Perkins			
Preplant	Midseason[¥]	2004	2005	2006	**Avg.**	2004	2005	2006	**Avg.**	2004	2005	2006	**Avg.**
---------kg N ha^{-1}---------		------------------------------------Total N Applied, kg ha^{-1}--											
0	0	0	0	0	**0**	0	0	0	**0**	0	0	0	**0**
0	67	67	67	67	**67**	67	67	67	**67**	67	67	67	**67**
0	134	134	134	134	**134**	134	134	134	**134**	134	134	134	**134**
67	67	134	134	134	**134**	134	134	134	**134**	134	134	134	**134**
67	0	67	67	67	**67**	67	67	67	**67**	67	67	67	**67**
134	0	134	134	134	**134**	134	134	134	**134**	134	134	134	**134**
0	RICV-NFOA	108	100	58	**89**	80	38	58	**59**	80	43	58	**67**
67	RICV-NFOA	168	194	119	**160**	152	90	103	**115**	168	147	119	**143**
0	Flat-RICV-NFOA	108	100	58	**89**	80	38	48	**55**	80	43	58	**67**
67	Flat-RICV-NFOA	168	194	119	**160**	152	90	106	**116**	168	147	119	**143**
67	RICV-NFOA	166	199	125	**163**	154	68	86	**103**	176	102	125	**126**
0	RI-NFOA	31	66	48	**48**	48	98	87	**78**	66	64	48	**62**
67	RI-NFOA	99	133	91	**108**	117	174	110	**134**	150	152	91	**131**

¥ Full description is presented in Table 2.

Table 10. Average, minimum and maximum midseason nitrogen rates for five treatments employing the nitrogen fertilization optimization algorithms at three locations, 2004-2006.

TRT No	Preplant kg ha^{-1}	NFOA	Resolution m^2	Efaw Min	Efaw Max	Efaw Avg.	Lake Carl Blackwell Min	Lake Carl Blackwell Max	Lake Carl Blackwell Avg.	Perkins Min	Perkins Max	Perkins Avg.
				---------------------- Sidedress N Rate, kg ha^{-1}--------------------------								
2004												
7	0	RICV	0.34	30	119	86	0	116	71	0	157	81
8	67	RICV	0.34	0	115	76	2	127	76	0	165	101
11	67	RICV	2.32	40	108	93	60	102	78	57	150	110
12	0	RI	0.34	17	46	32	22	56	43	39	88	66
13	67	RI	0.34	28	42	35	20	55	44	40	92	80
2005												
7	0	RICV	0.34	0	157	90	0	125	34	0	93	38
8	67	RICV	0.34	0	163	113	0	110	20	0	201	71
11	67	RICV	2.32	21	151	118	0	4	0	0	76	31
12	0	RI	0.34	20	80	58	0	108	88	39	89	58
13	67	RI	0.34	23	78	59	67	110	95	44	105	76
2006												
7	0	RICV	0.34	0	136	52	0	177	52	0	189	69
8	67	RICV	0.34	0	45	46	0	99	32	0	126	42
11	67	RICV	2.32	0	104	52	0	11	40	6	62	28
12	0	RI	0.34	20	70	43	33	127	78	23	102	50
13	67	RI	0.34	10	31	21	11	58	38	8	40	20

NFOA = nitrogen fertilization optimization algorithm
RICV = NFOA refined by response index and coefficient of variation as components
RI = NFOA refined by response index

Table 11. Total nitrogen uptake in response to fixed and midseason NFOA-based N rates at Efaw, Lake Carl Blackwell and Perkins, 2004-2006.

N Applied		Efaw				Lake Carl Blackwell				Perkins			
Preplant	Midseason[¥]	2004	2005	2006	**Avg.**	2004	2005	2006	**Avg.**	2004	2005	2006	**Avg.**
---------kg N ha^{-1}---------		--Total N Uptake, kg ha^{-1}--											
0	0	126	88	81	**98**	49	131	38	**73**	65	22	16	**34**
0	67	173	139	137	**149**	106	177	98	**127**	90	62	36	**63**
0	134	172	147	137	**152**	119	202	181	**168**	112	68	48	**76**
67	67	190	164	157	**170**	135	209	150	**165**	135	87	57	**93**
67	0	186	131	126	**148**	109	175	54	**113**	100	70	49	**73**
134	0	165	173	190	**176**	126	216	138	**160**	116	72	41	**76**
0	RICV-NFOA	160	133	108	**134**	97	158	93	**116**	101	63	51	**72**
67	RICV-NFOA	177	187	178	**181**	131	184	99	**138**	127	83	53	**87**
0	Flat-RICV-NFOA	179	135	142	**152**	101	150	93	**115**	105	43	39	**62**
67	Flat-RICV-NFOA	185	180	169	**178**	140	177	113	**143**	131	75	41	**83**
67	RICV-NFOA	185	176	172	**178**	140	187	78	**135**	139	77	41	**86**
0	RI-NFOA	167	145	124	**145**	101	187	143	**144**	93	57	36	**62**
67	RI-NFOA	222	186	193	**200**	128	218	139	**162**	130	85	44	**86**
Pr>F		0.1124	0.0008	0.0052	-	0.0001	0.0205	0.0001	-	0.0001	0.0001	0.0308	-
SED		16	16.3	24	-	7.6	15.8	15.2	-	5.8	6.2	6.8	-

SED = Standard error of the difference between two equally replicated means

¥ Full description is presented in Table 2.

Table 12. Nitrogen use efficiency in response to fixed and midseason NFOA-based N rates at Efaw, Lake Carl Blackwell and Perkins, 2004-2006.

N Applied		Efaw				Lake Carl Blackwell				Perkins			
Preplant	Midseason¥	2004	2005	2006	**Avg.**	2004	2005	2006	**Avg.**	2004	2005	2006	**Avg.**
---------kg N ha^{-1}---------		------------------------------------Nitrogen Use Efficiency§, %--											
0	0	-	-	-	-	-	-	-	-	-	-	-	-
0	67	71	69	67	**69**	86	52	88	**75**	38	60	30	**43**
0	134	35	44	43	**41**	53	53	98	**68**	35	34	24	**31**
67	67	48	57	57	**54**	65	57	84	**69**	52	49	30	**44**
67	0	64	52	58	**58**	89	65	26	**60**	52	71	50	**58**
134	0	30	63	81	**58**	57	63	70	**63**	38	38	18	**31**
0	RICV-NFOA	32	50	58	**47**	60	33	84	**59**	45	86	46	**59**
67	RICV-NFOA	31	52	73	**52**	55	58	63	**59**	37	42	32	**37**
0	Flat-RICV-NFOA	50	51	68	**56**	67	33	86	**62**	51	49	32	**44**
67	Flat-RICV-NFOA	35	49	66	**50**	60	40	69	**57**	39	37	22	**33**
67	RICV-NFOA	35	46	72	**51**	59	76	47	**60**	42	56	25	**41**
0	RI-NFOA	79	73	79	**77**	96	57	98	**83**	40	53	35	**43**
67	RI-NFOA	77	74	98	**83**	68	50	88	**69**	43	42	31	**39**
Pr>F		0.0351	0.7280	0.6010	-	0.0002	0.5992	0.0556	-	0.6900	0.0032	0.2895	-
SED		12	17	20	-	6	21	16.2	-	12	8	8.6	-

§ Estimated by subtracting the grain N uptake of the check plot from the fertilized plot, divided by the N rate applied.
SED = Standard error of the difference between two equally replicated means
¥ Full description is presented in Table 2.

Table 13. Net return to nitrogen fertilizer at Efaw, Lake Carl Blackwell and Perkins, 2004-2006.

N Applied		Efaw				Lake Carl Blackwell				Perkins			
Preplant	Midseason[¥]	2004	2005	2006	**Avg.**	2004	2005	2006	**Avg.**	2004	2005	2006	**Avg.**
---------kg N ha^{-1}---------		---------Net Return[‡], $ ha^{-1}---------											
0	0	990	608	726	**775**	433	975	628	**679**	556	182	257	**332**
0	67	1325	925	1199	**1150**	747	1186	994	**976**	672	356	253	**427**
0	134	1148	899	1071	**1039**	665	1266	1318	**1083**	664	277	279	**407**
67	67	1315	913	1175	**1134**	841	1306	1191	**1112**	831	420	333	**528**
67	0	1249	852	1040	**1047**	780	1215	722	**906**	752	436	364	**517**
134	0	1303	1007	1407	**1239**	738	1303	1112	**1051**	753	323	230	**435**
0	RICV-NFOA	1100	767	876	**914**	595	1148	966	**903**	687	372	365	**475**
67	RICV-NFOA	1346	1035	1382	**1254**	721	1214	969	**968**	723	394	314	**477**
0	Flat-RICV-NFOA	1338	847	1169	**1118**	641	1065	977	**894**	684	296	260	**413**
67	Flat-RICV-NFOA	1289	987	1275	**1184**	811	1210	1032	**1018**	742	382	227	**450**
67	RICV-NFOA	1289	974	1252	**1171**	801	1277	842	**974**	777	404	254	**478**
0	RI-NFOA	1319	941	1193	**1151**	681	1289	1193	**1054**	657	289	255	**401**
67	RI-NFOA	1397	1118	1517	**1344**	803	1302	1161	**1089**	787	368	285	**480**
Pr>F		0.0245	0.0127	0.0443	-	0.0001	0.0618	0.0002	-	0.0013	0.0003	0.8147	-
SED		73	82	171	-	60	73	83	-	37	31	60	-

‡ Determined by subtracting the cost of fertilizer from the gross income (grain yield x price per unit grain). Prices of grain and fertilizer are reported in Table 5.

¥ Full description is presented in Table 2.

SED = Standard error of the difference between two equally replicated means

VITA

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Doctor of Philosophy

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Pages in Study: 66 Candidate for the Degree of Doctor of Philosophy

Major Field: Soil Science

Scope and Method of Study: For chapter one, resolution trials were conducted to determine the scale at which spatial variability in winter wheat should be treated using an in-season nitrogen fertilization optimization algorithm (NFOA). The treatments included variable N rate applications at three resolutions (0.84, 13.37, and 26.76 m^2), a fixed N rate at 90 kg ha^{-1} applied preplant and midseason, and a check plot arranged in a completely randomized design with three replications. For chapter two, experiments were conducted to formulate an in-season NFOA to estimate midseason N rates that maximize corn growth and minimize inputs, and to determine the optimum resolution to treat spatial variability in corn. The experiment consisted of 13 treatments arranged in a randomized block design with three replications. Treatments included: a 134 kg N ha^{-1} fixed rate applied in split, preplant- and sidedress-only; a 67 kg N ha^{-1} fixed rate applied preplant- and sidedress-only; three NFOA-based midseason N rates (RICV-, RI- and flat-RICV-NFOA) with (67 kg N ha^{-1}) and without preplant N; and two resolutions (0.34 and 2.32 m^2) tested for RICV-NFOA only.

Findings and Conclusions: For chapter one, the NFOA-based N rates achieved a higher N use efficiency (NUE) value of 41% compared with 33% of the 90 kg N ha^{-1} fixed rate applied midseason. Treating spatial variability using NFOA at 13.4 m^2 achieved the highest NUE value of 56%. Four out of six site years resulted in a higher net return ($ 5 to 101 ha^{-1}) when an NFOA approach was used. Treating spatial variability at 13.4 m^2 using the NFOA resulted in increased NUE and net return. For chapter two, with 67 kg N ha^{-1} preplant application, midseason RI-NFOA-based N rates improved NUE to 64% when compared with 56% of the134 kg N ha^{-1} fixed rate split applied. The RI-NFOA midseason N rates resulted in higher grain yield and net return in three of six high yielding site years. In general, the use of midseason N rate recommendations based on N demand of predicted yield potential resulted in improved NUE and net return compared with fixed N fertilizer application at 134 kg N ha^{-1}.

ADVISER'S APPROVAL: DR. WILLIAM R. RAUN